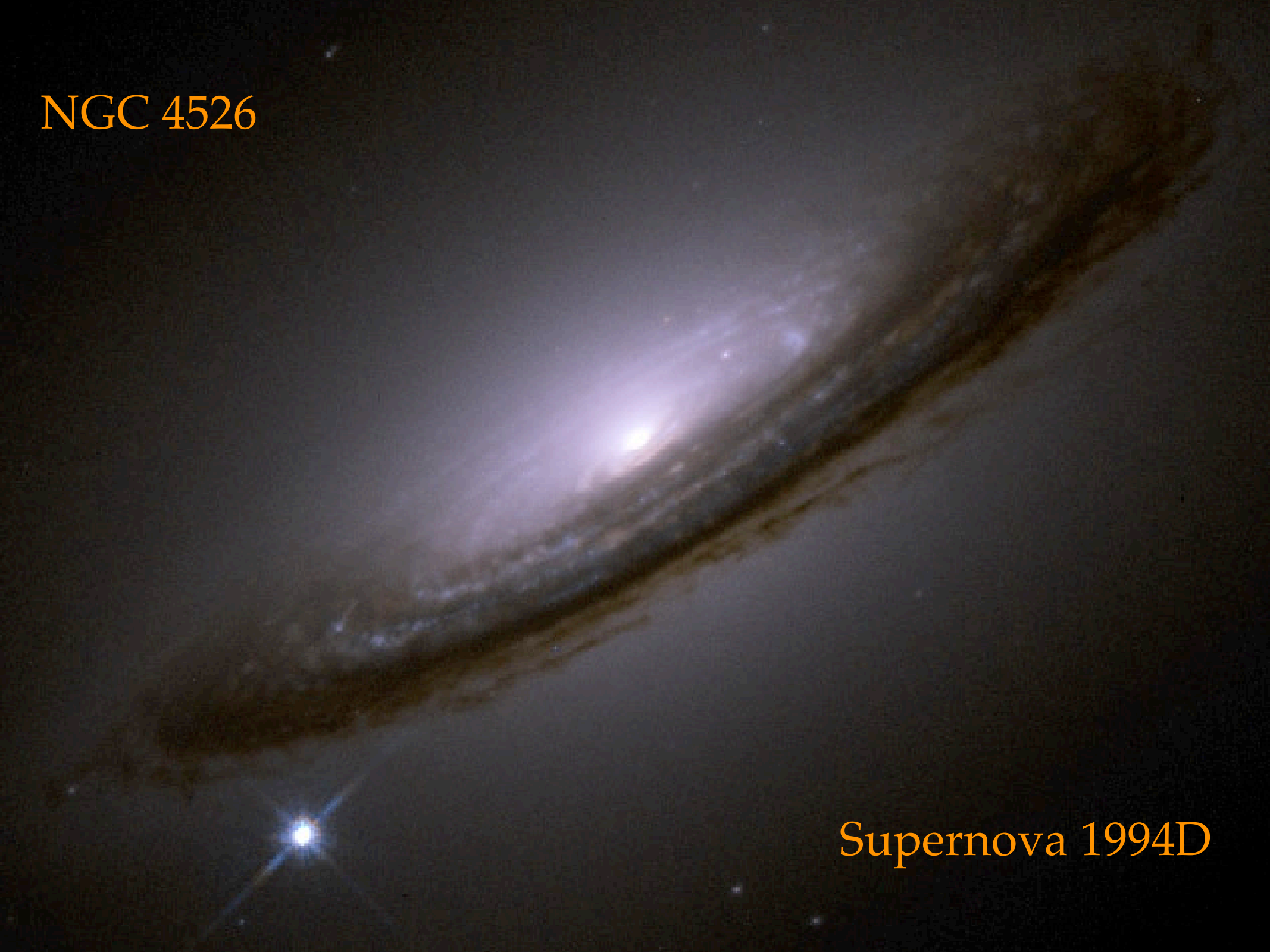
The Search For Dark Energy

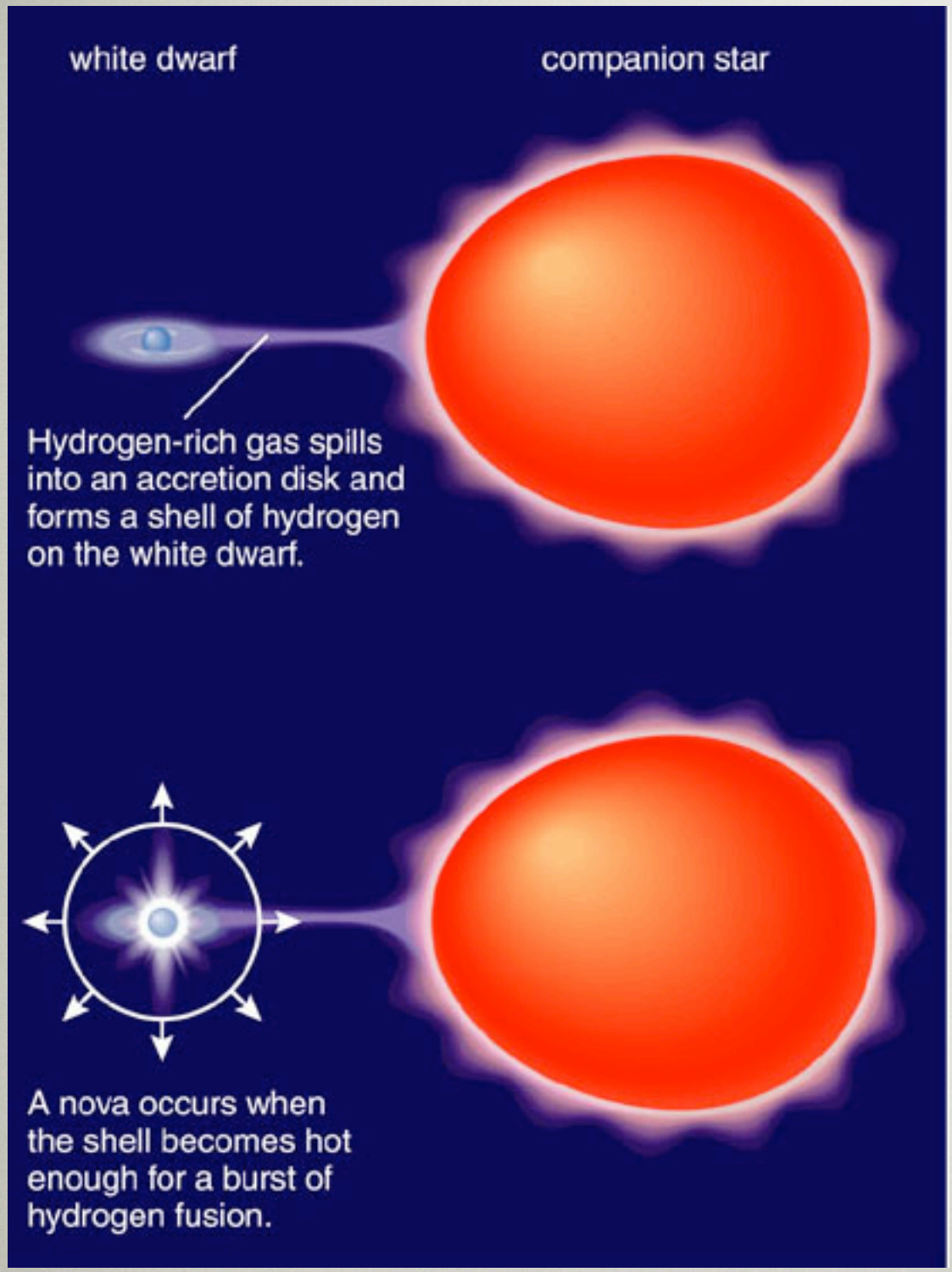
James Annis
Experimental Astrophysics/Fermilab


The Universe
Our Instrumentation

Supernovae

The Triumph of Classical Astronomy


NGC 4526
Supernova 1994D

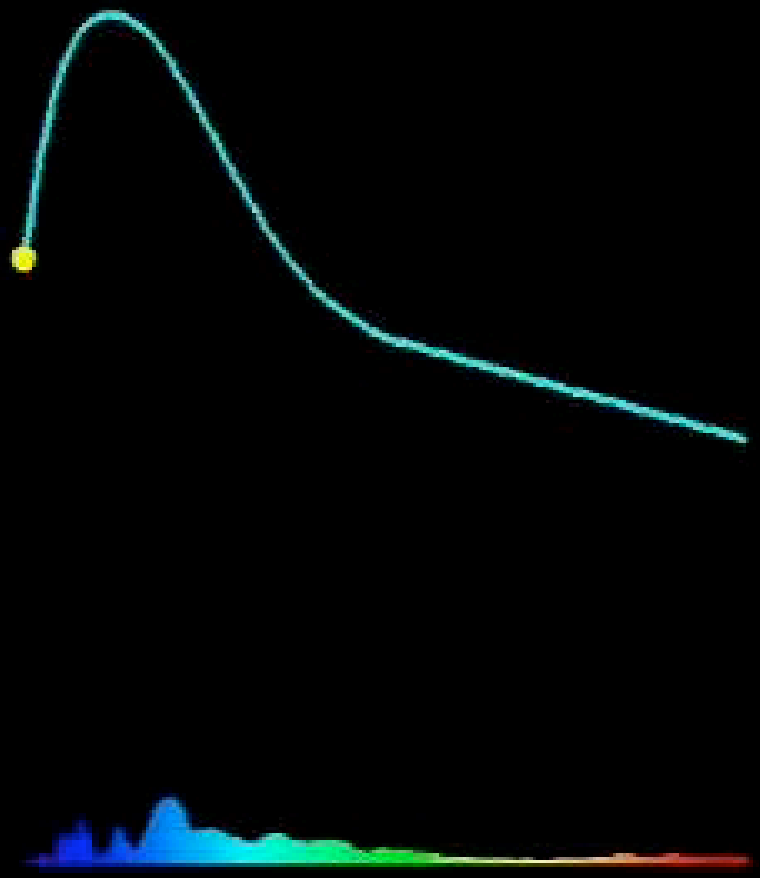


Type 1a supernovae are white dwarf bombs.

Mass transfered from a neighbor star increases the white dwarf mass over the Chandrasakar Limit, and the white dwarf drops to a neutron star. This is a supernova.

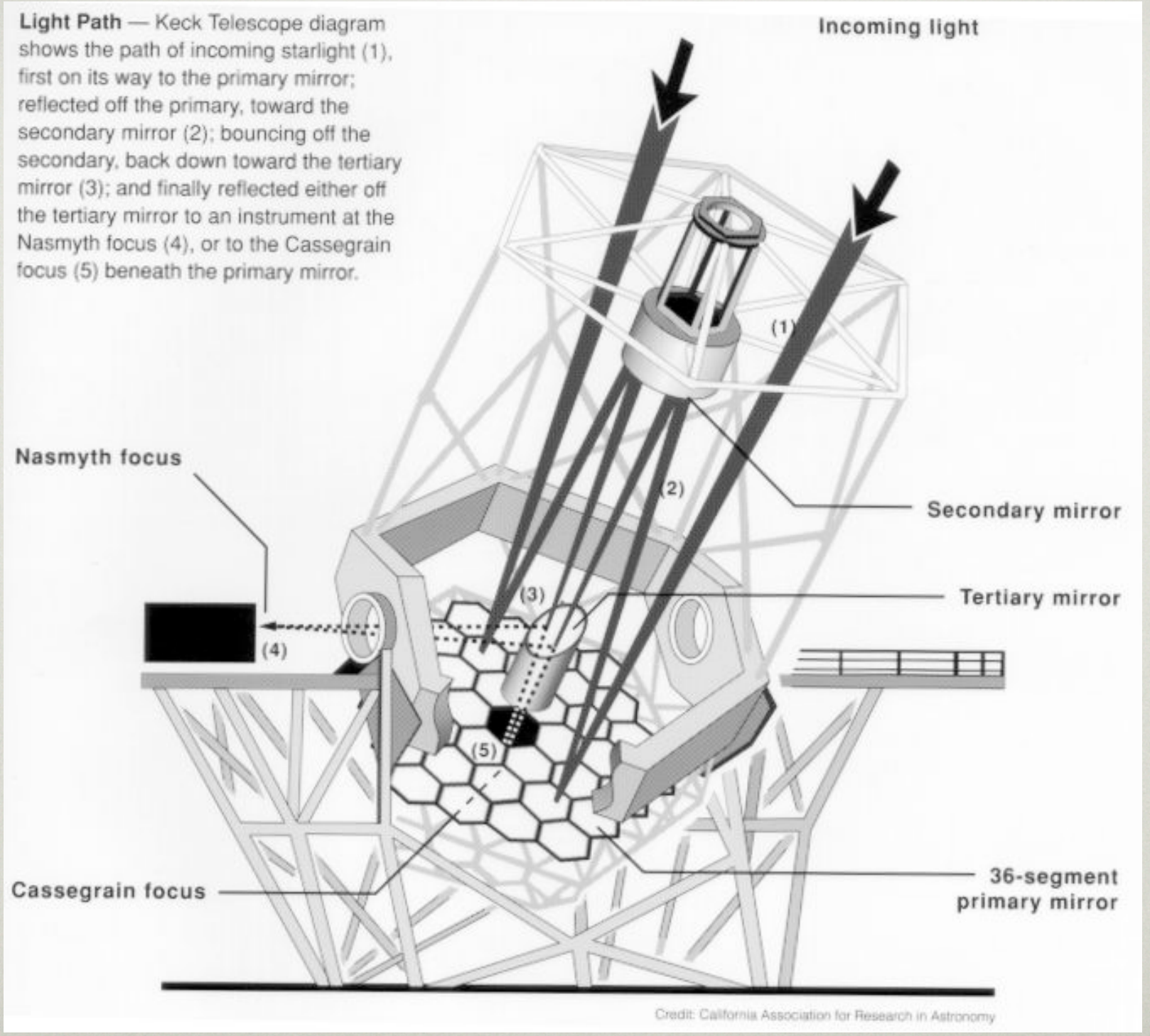
Courtesy: people.brandeis.edu/ ~wardle/ch18/chapter-18.html

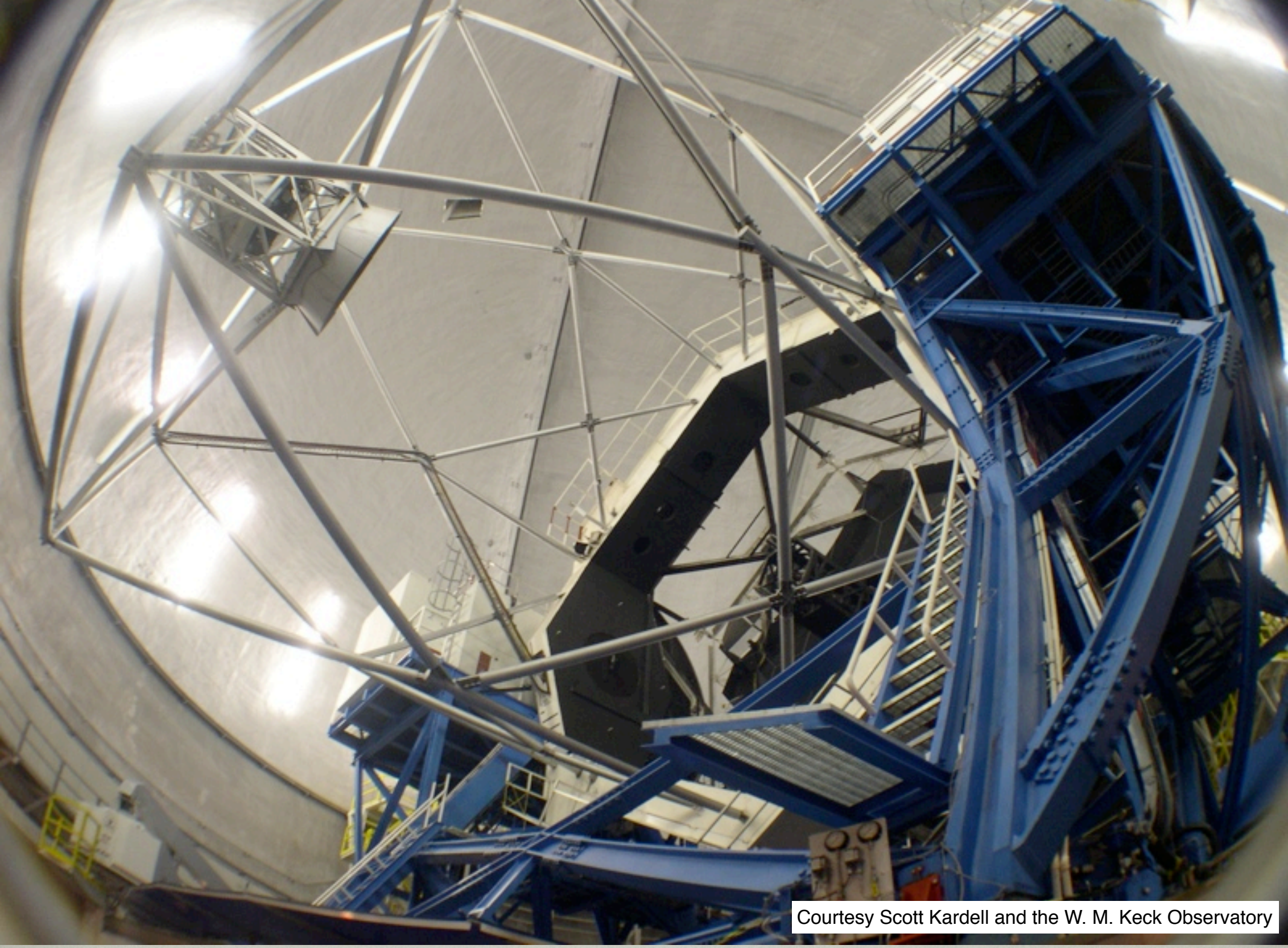
A Supernova brightens and dims over a month,
but the peak brightness is constant- a standard candle.



The Keck 10m Telescopes

The pursuit of SN requires big glass.

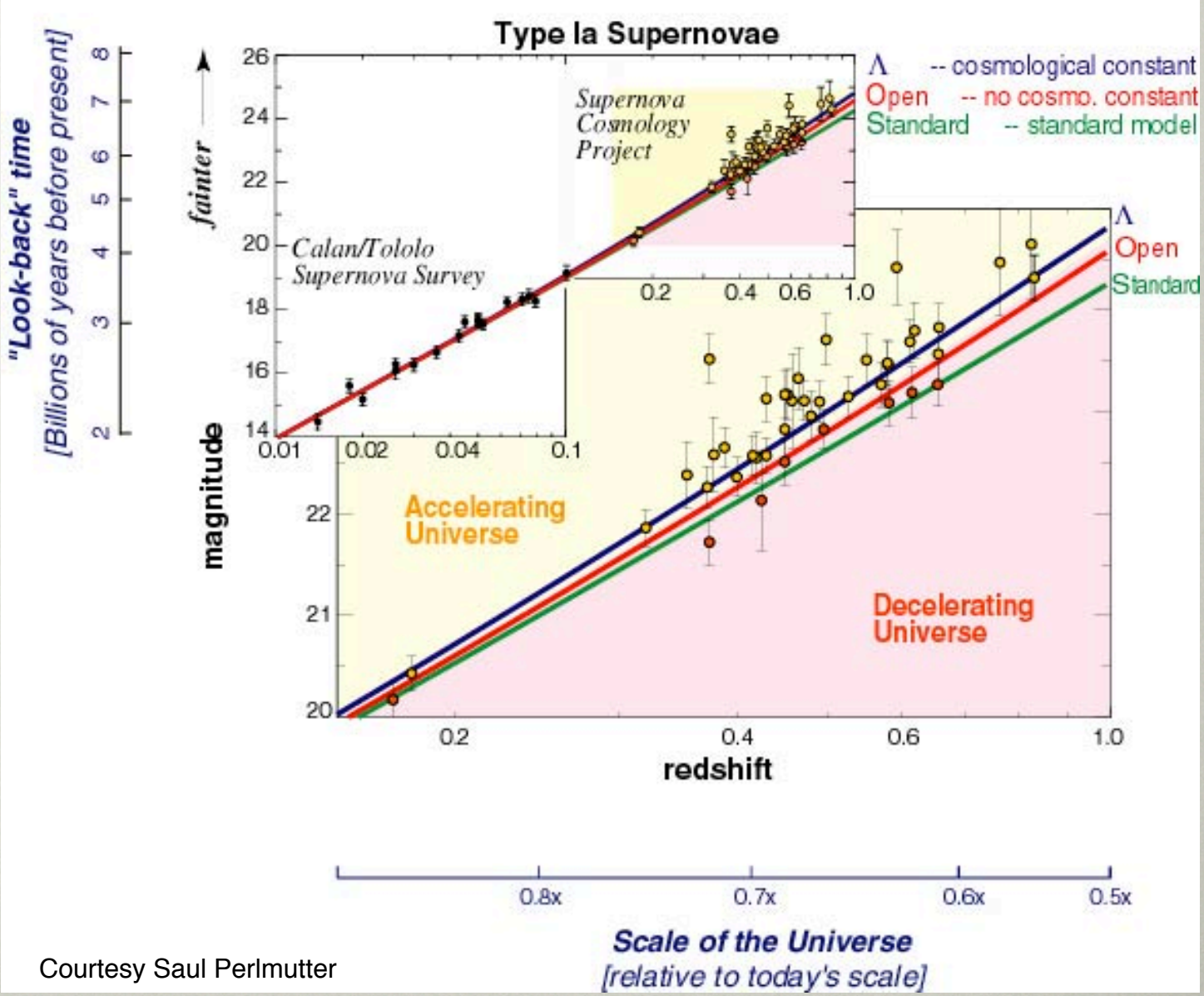

Light Path — Keck Telescope diagram shows the path of incoming starlight (1), first on its way to the primary mirror; reflected off the primary, toward the secondary mirror (2); bouncing off the secondary, back down toward the tertiary mirror (3); and finally reflected either off the tertiary mirror to an instrument at the Nasmyth focus (4), or to the Cassegrain focus (5) beneath the primary mirror.
Incoming light
(1)
(2)
Secondary mirror
Nasmyth focus
(3)
Tertiary mirror
(4)
(5)
Cassegrain focus
36-segment primary mirror
Credit: California Association for Research in Astronomy



Courtesy Scott Kardell and the W. M. Keck Observatory

Supernovae Distances measure the Geometry of the Universe

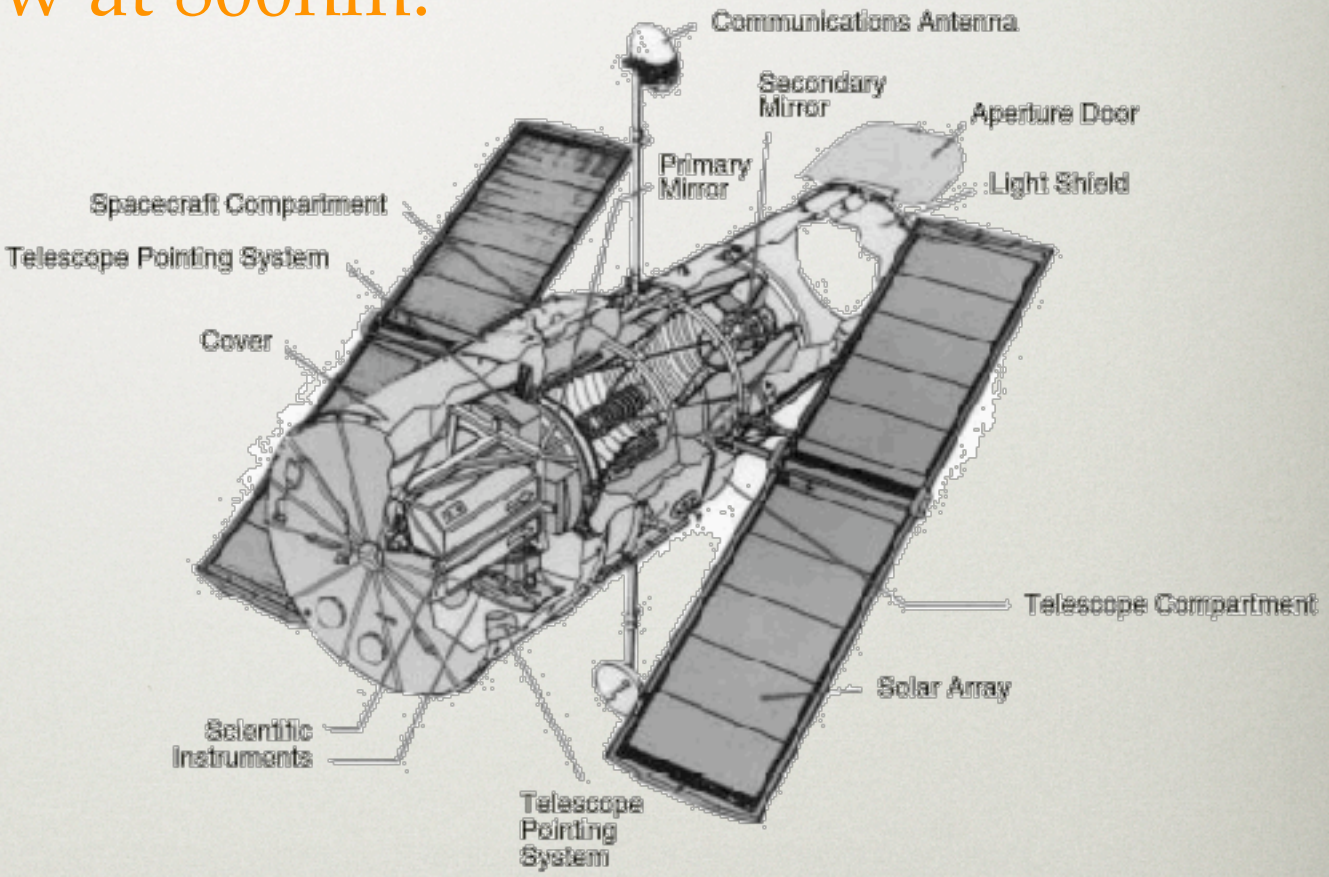
Big glass is needed to follow SN to high redshift where their apparent brightness tells us about distance.



Courtesy Saul Perlmutter

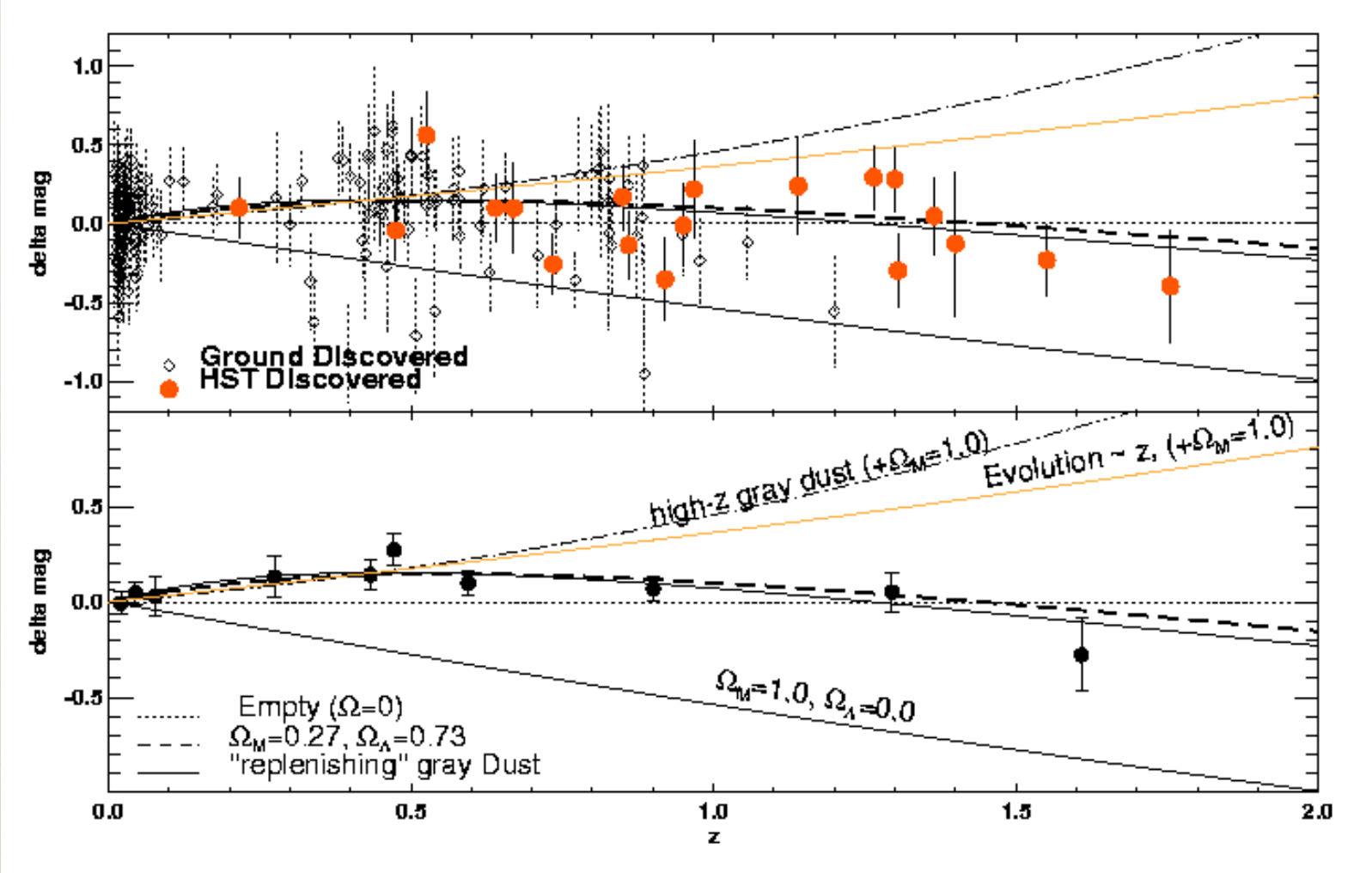
The Hubble Space Telescope: 2.2m

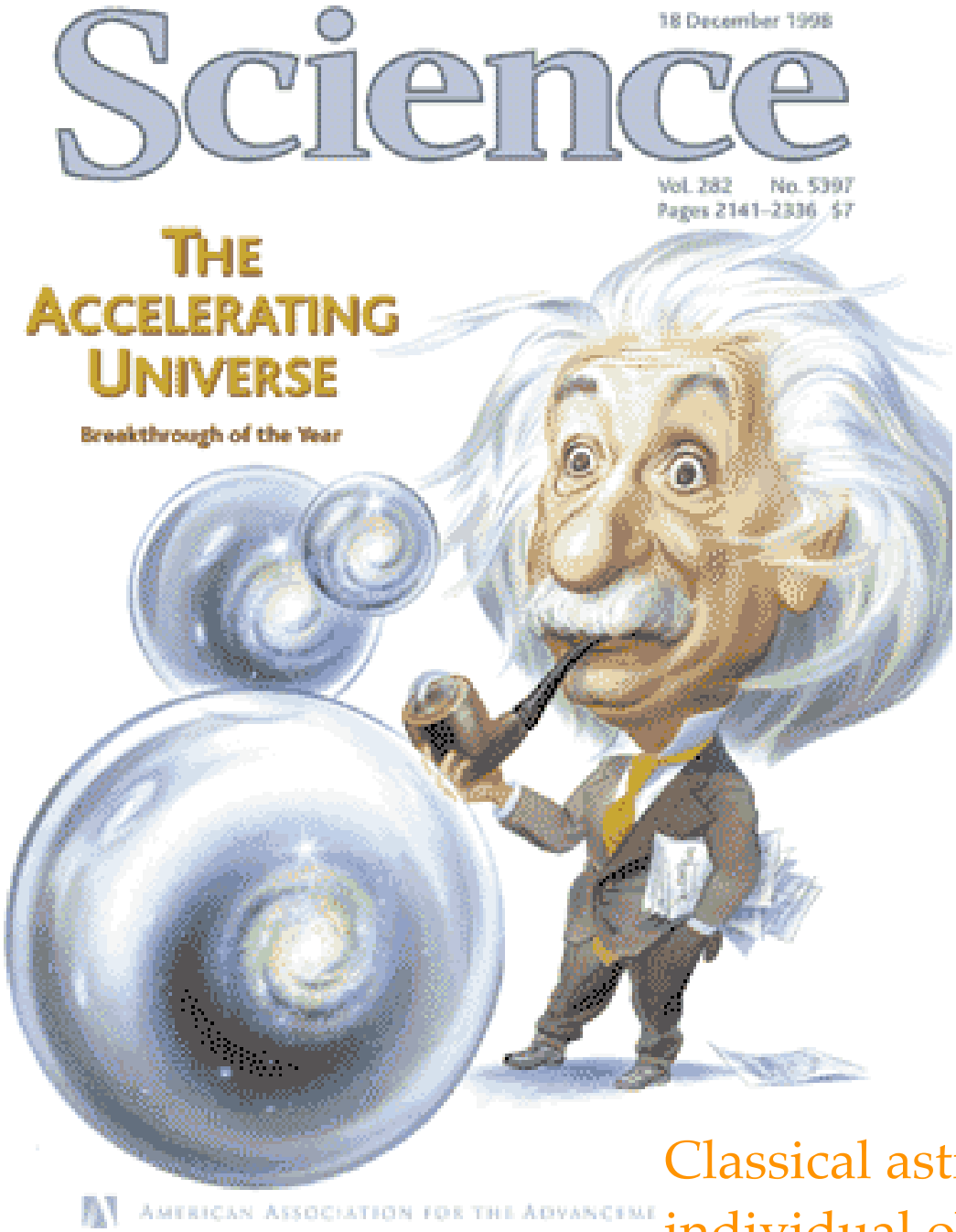
Glass in space is needed to bypass the atmospheric glow at 800nm.



STS103-713-048
(19-27 December 1999) --- Astronauts Steven L. Smith,and John M. Grunsfeld are replacing gyroscopes, contained in rate sensor units (RSU), inside the Hubble Space Telescope.

HST high-z observations showed the effect behaved like a modification to the geometry





Two independent, in fact rival, teams measured supernova at high redshift.

The Supernova Cosmology Project, based at Lawrence Berkeley National Laboratory, and the High-Z Supernova Search Team based at the Mount Stromlo and Siding Spring Observatories in Australia, had assumed that expansion had been slowing under the gravitational attraction of matter since shortly after the Big Bang, and that this deceleration rate could be used to determine the average density of matter in the universe.

The last thing the two teams expected to find was that the expansion of the universe is not slowing at all. Instead, it is accelerating.

The astronomical community was convinced.

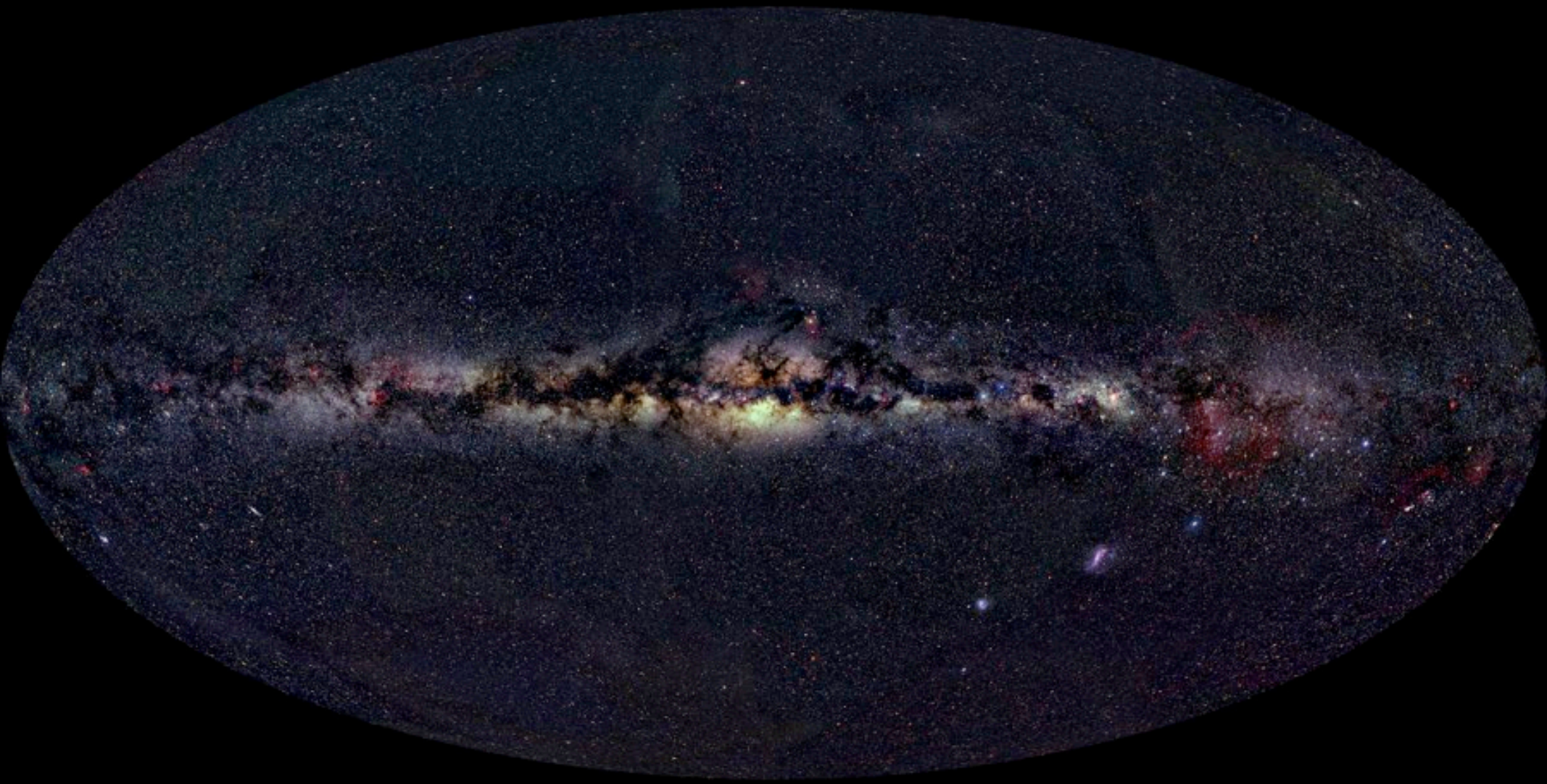
Classical astronomy, the use of big glass to study individual objects, achieves a triumph.

Galaxies

What we see in the universe

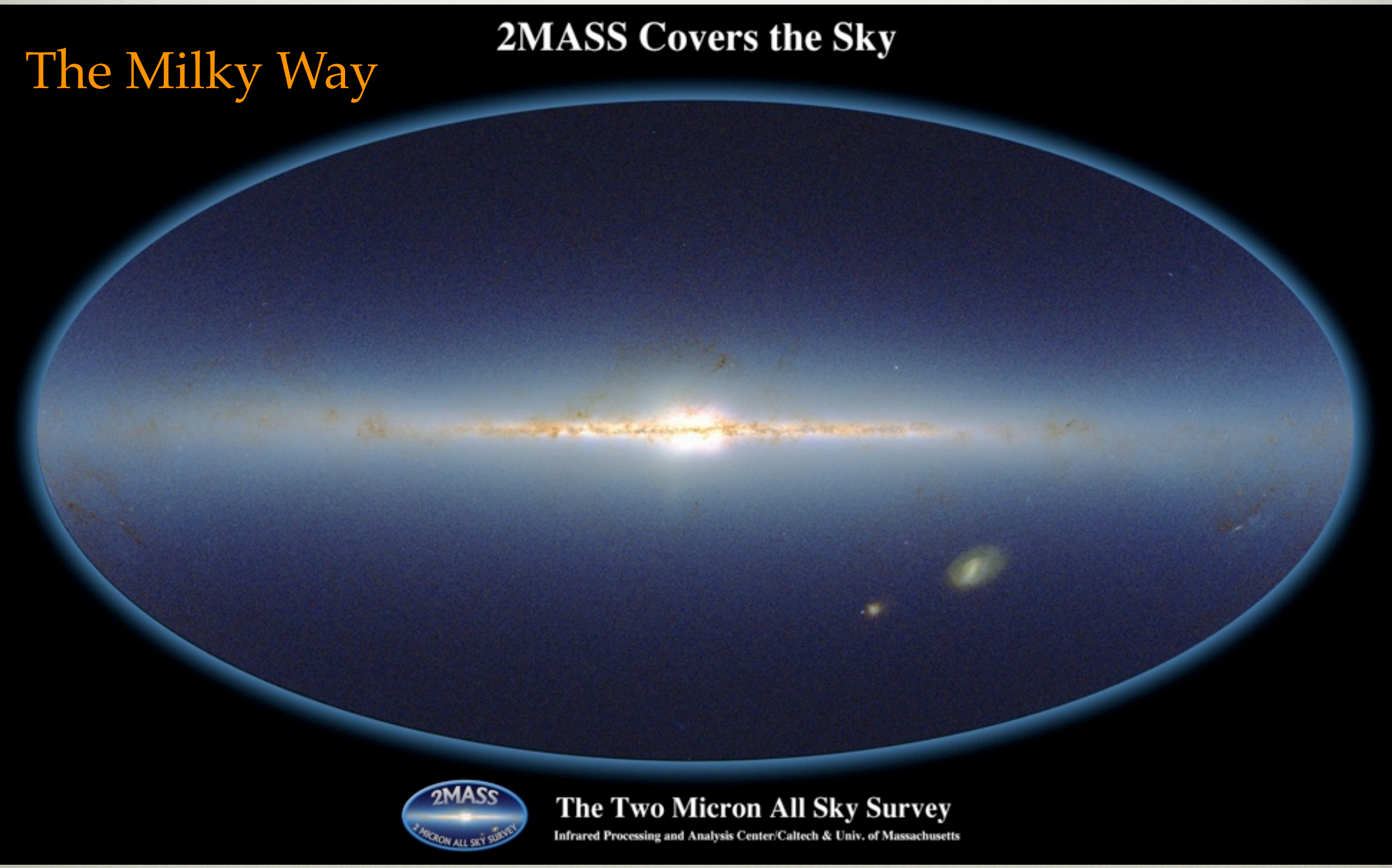
What You See at Night

The Milky Way



The Galaxy Cleaned Up

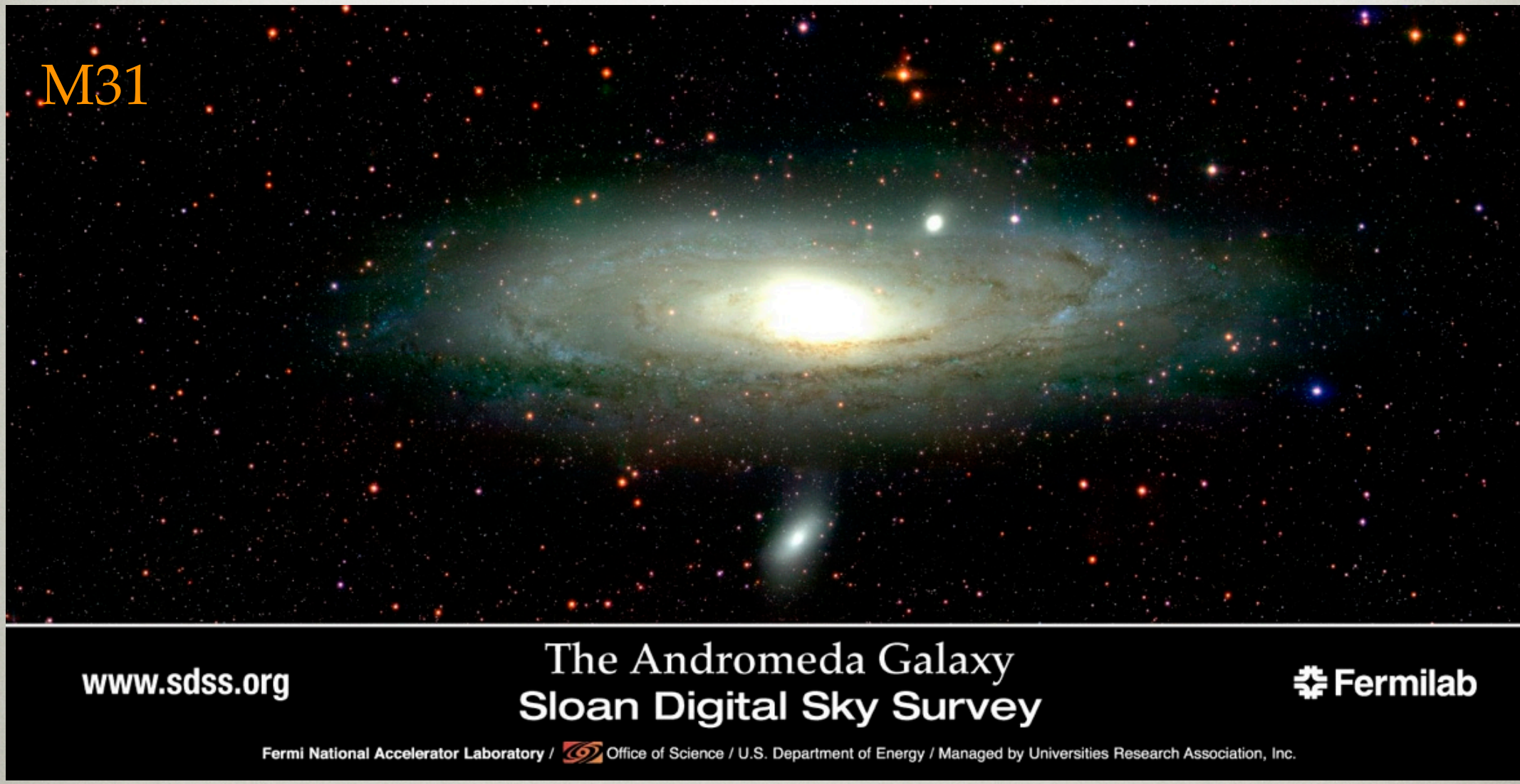
The Milky Way



NGC4565, a Milky Way Analog

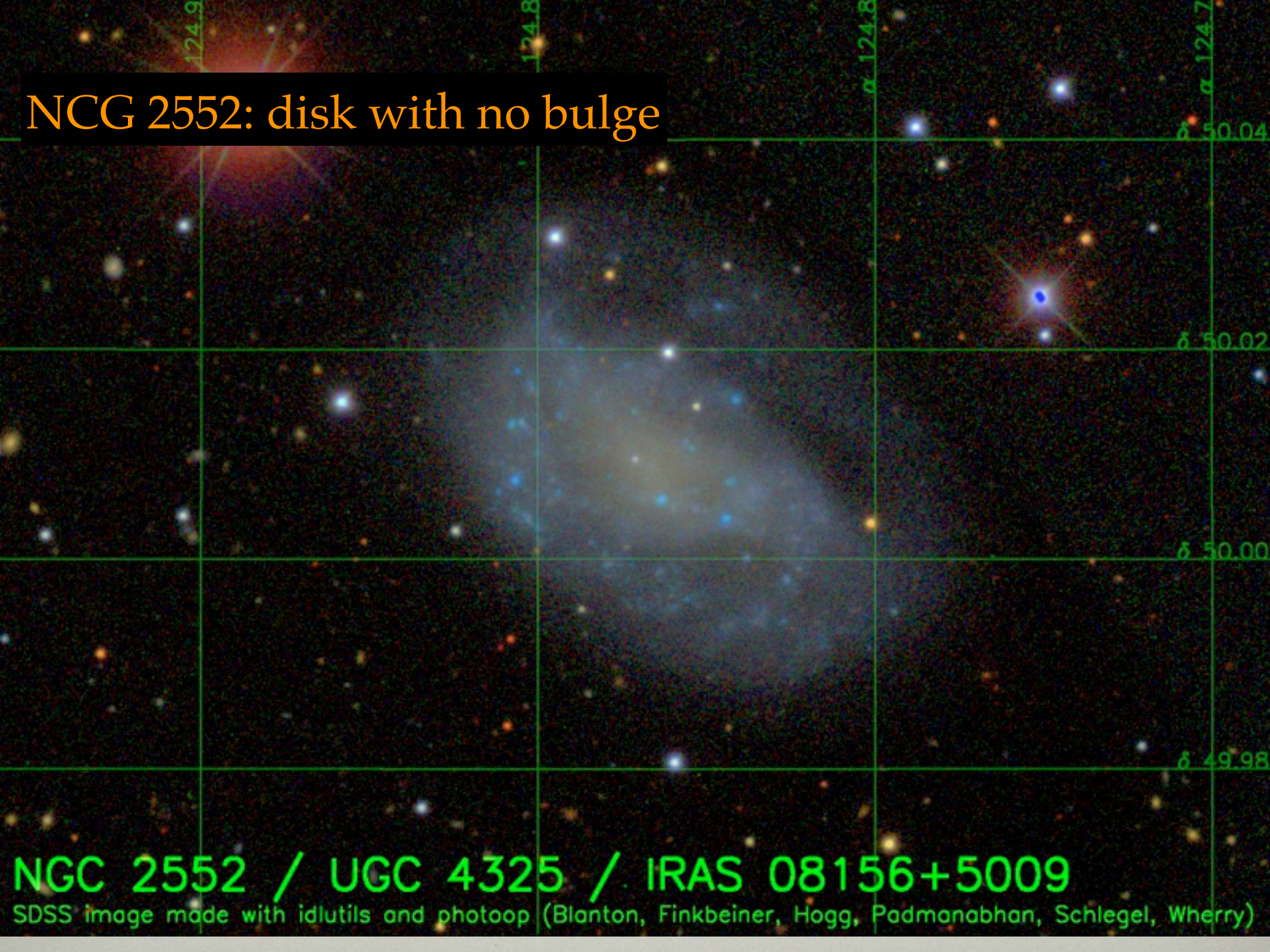
Courtesy: Bruce Hugo, Leslie Gaul, Adam Block, NOAO

The Closest Big Galaxy



NCG 1309: a disk galaxy face on

Courtesy: Hubble Heritage Project


NCG 2552: disk with no bulge
α 124.9
α 124.8
α 124.8
α 124.7
δ 50.04
δ 50.02
δ 50.00
δ 49.98
NGC 2552 / UGC 4325 / IRAS 08156+5009
SDSS image made with idlutils and photoop (Blanton, Finkbeiner, Hogg, Padmanabhan, Schlegel, Wherry)

Barred Spiral Galaxy NGC 1300

NCG 1300: a bar

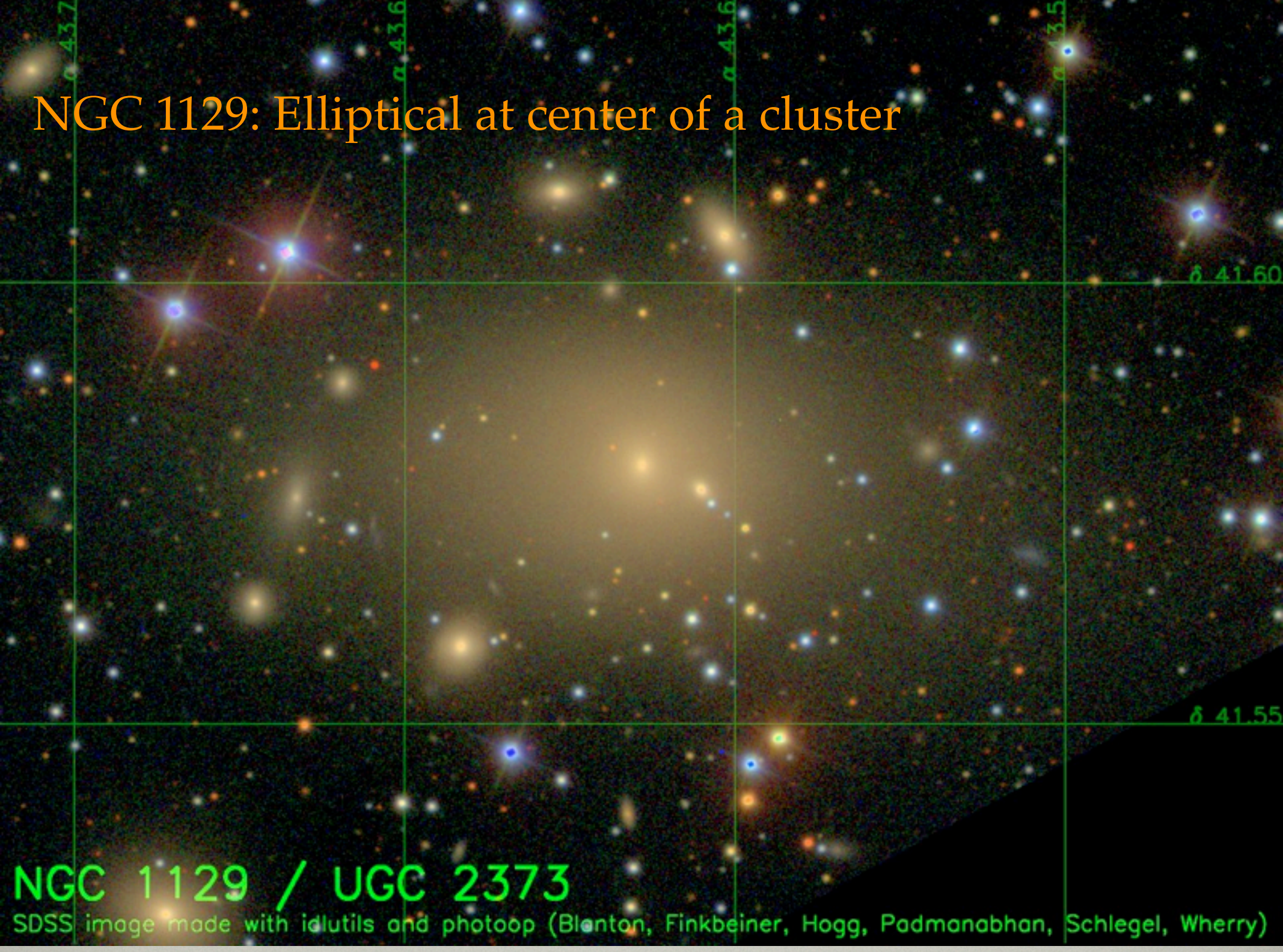
Hubble Heritage

NASA, ESA and The Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope ACS • STScI-PRC05-01

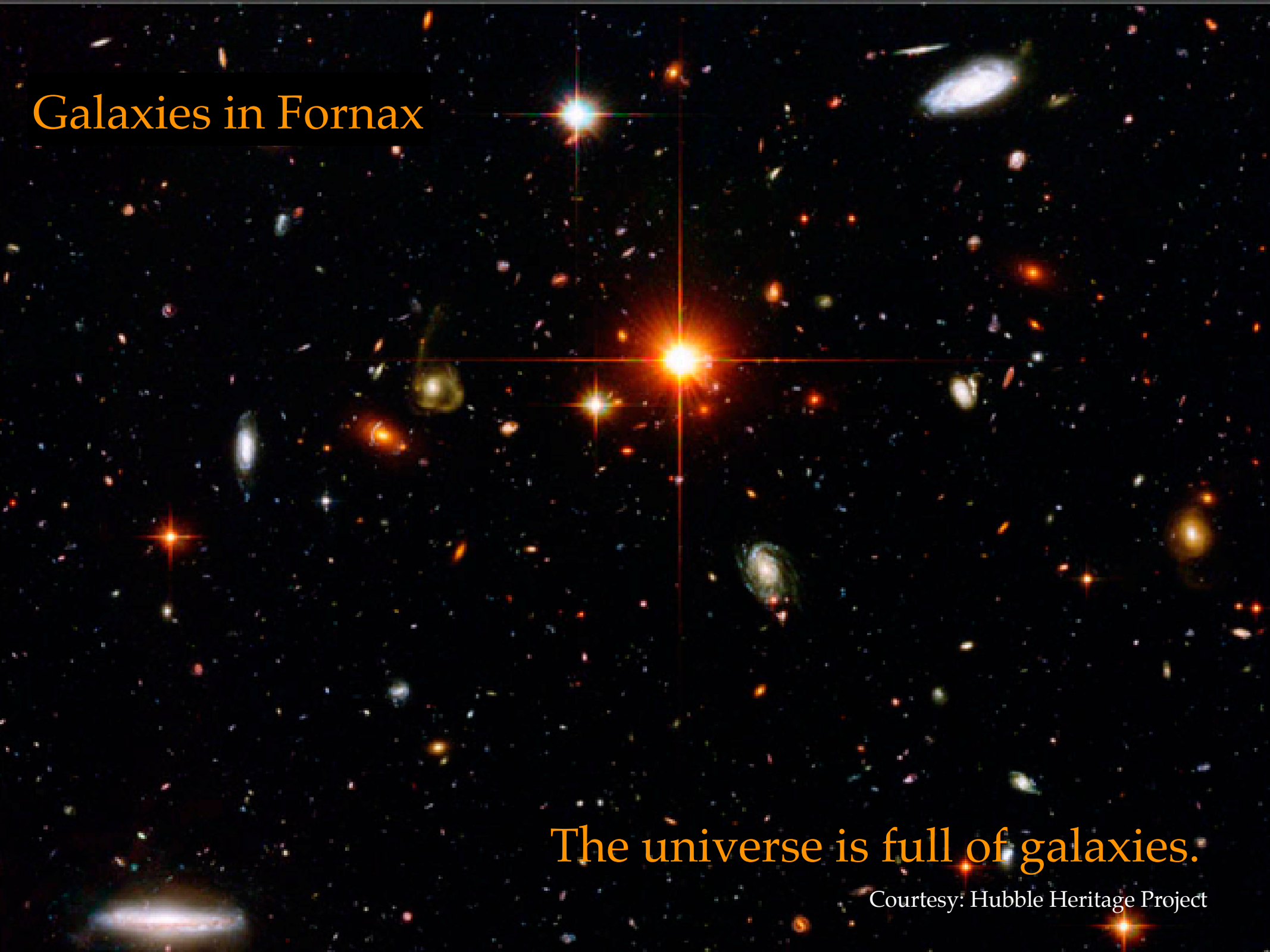
M104: Elliptical plus dust

Courtesy: Hubble Heritage Project

ESO 510-G13: Elliptical plus warped dust


NGC 1129: Elliptical at center of a cluster
α 43.7
α 43.6
α 43.6
α 43.5
δ 41.60
δ 41.55
NGC 1129 / UGC 2373
SDSS image made with idlutils and photoop (Blanton, Finkbeiner, Hogg, Padmanabhan, Schlegel, Wherry)

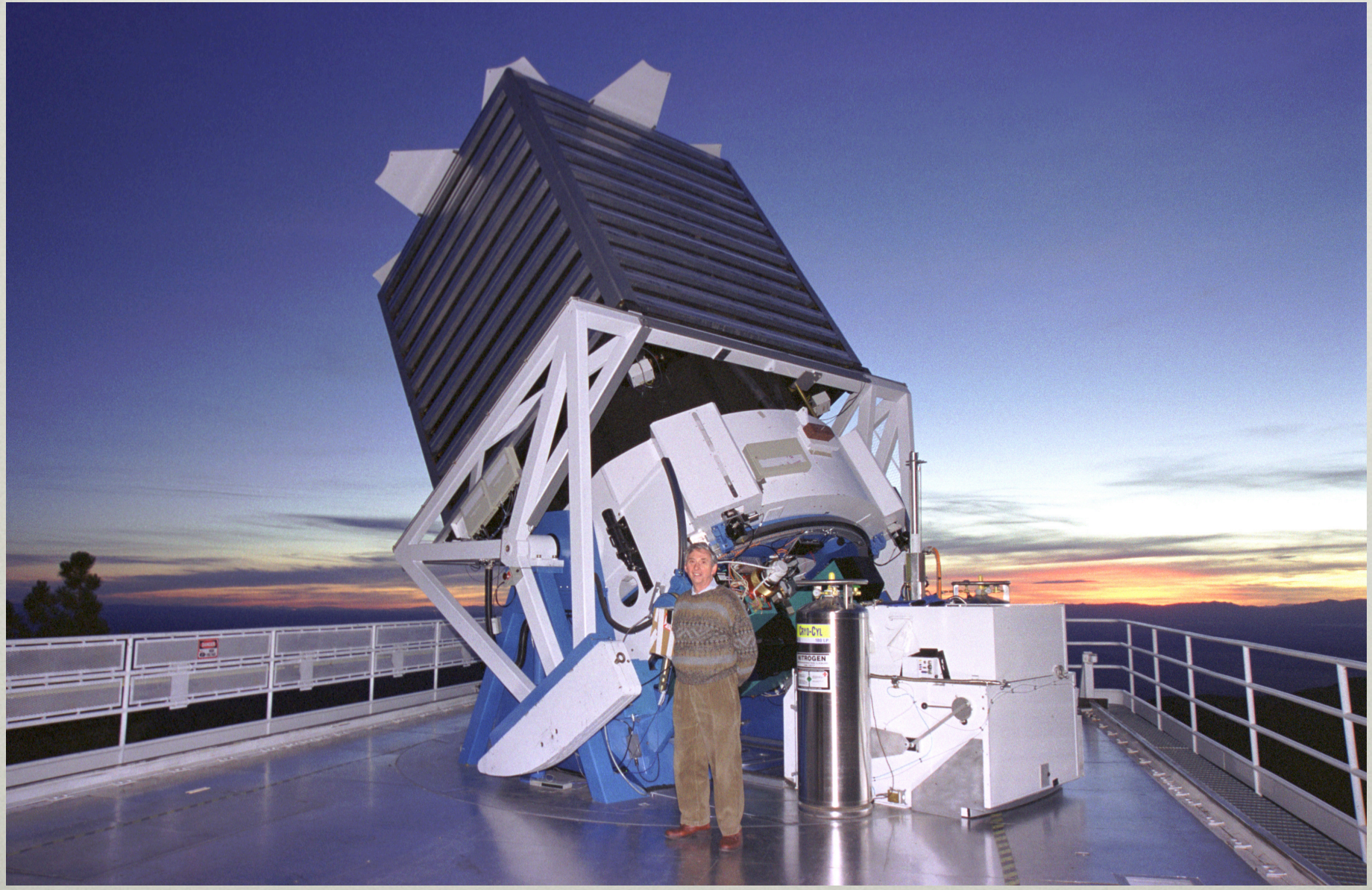

UGC 10214: disturbed galaxy
but look at all the other galaxies!
Courtesy: NASA ACS team


Galaxies in Fornax
The universe is full of galaxies.
Courtesy: Hubble Heritage Project

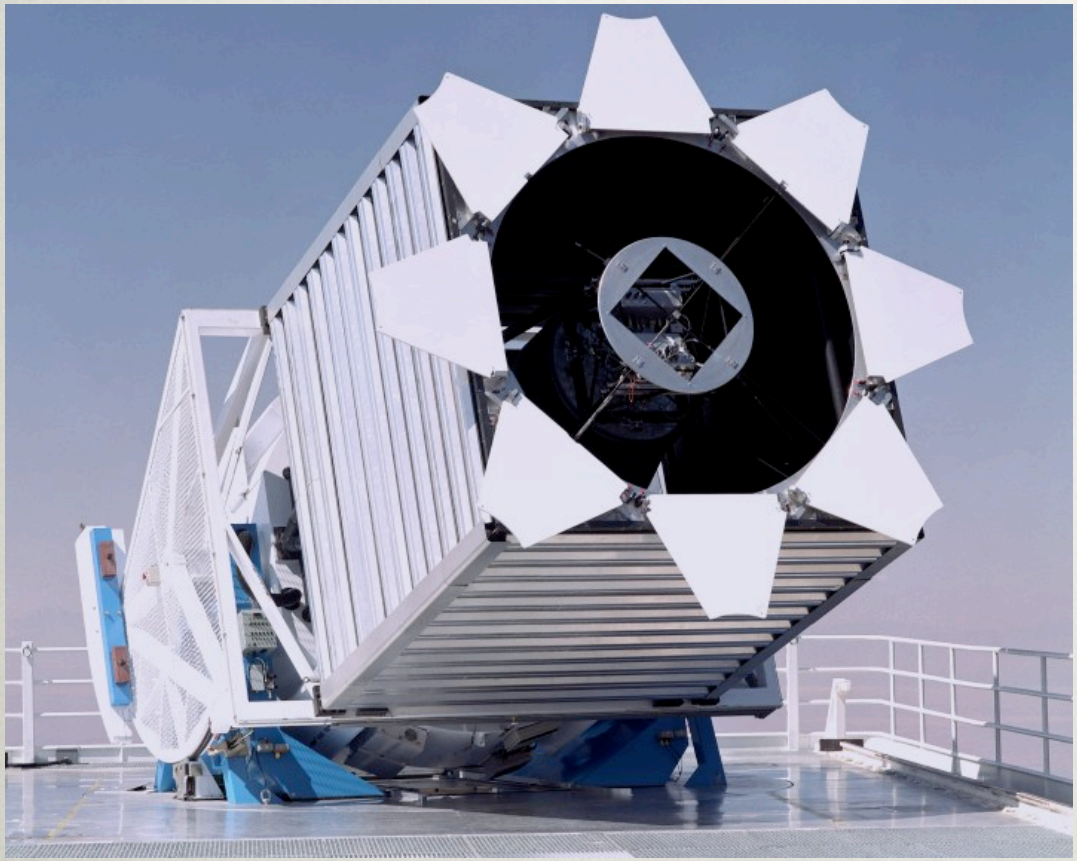
Galaxies in the Universe

The Rise of Statistical Cosmology

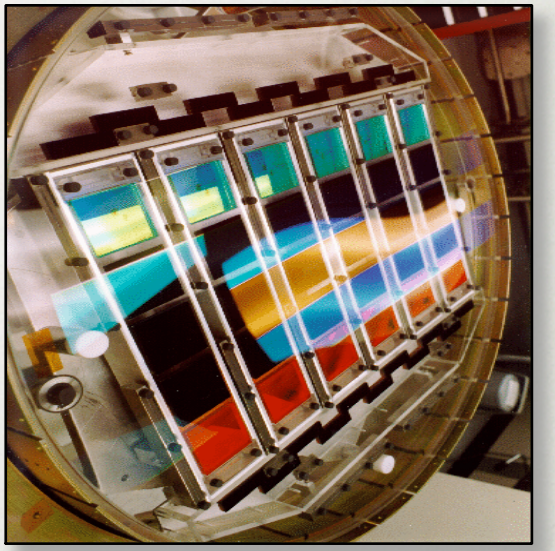
The Sloan Digital Sky Survey



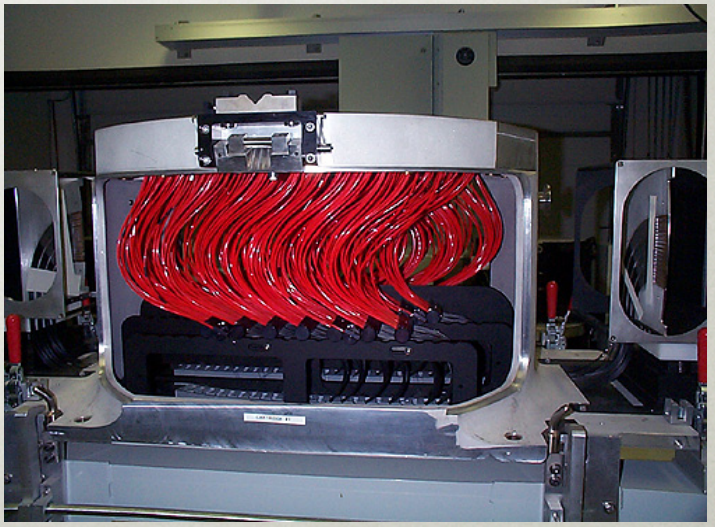
The SDSS Instrumentation



Dedicated 2.5 m wide-field telescope



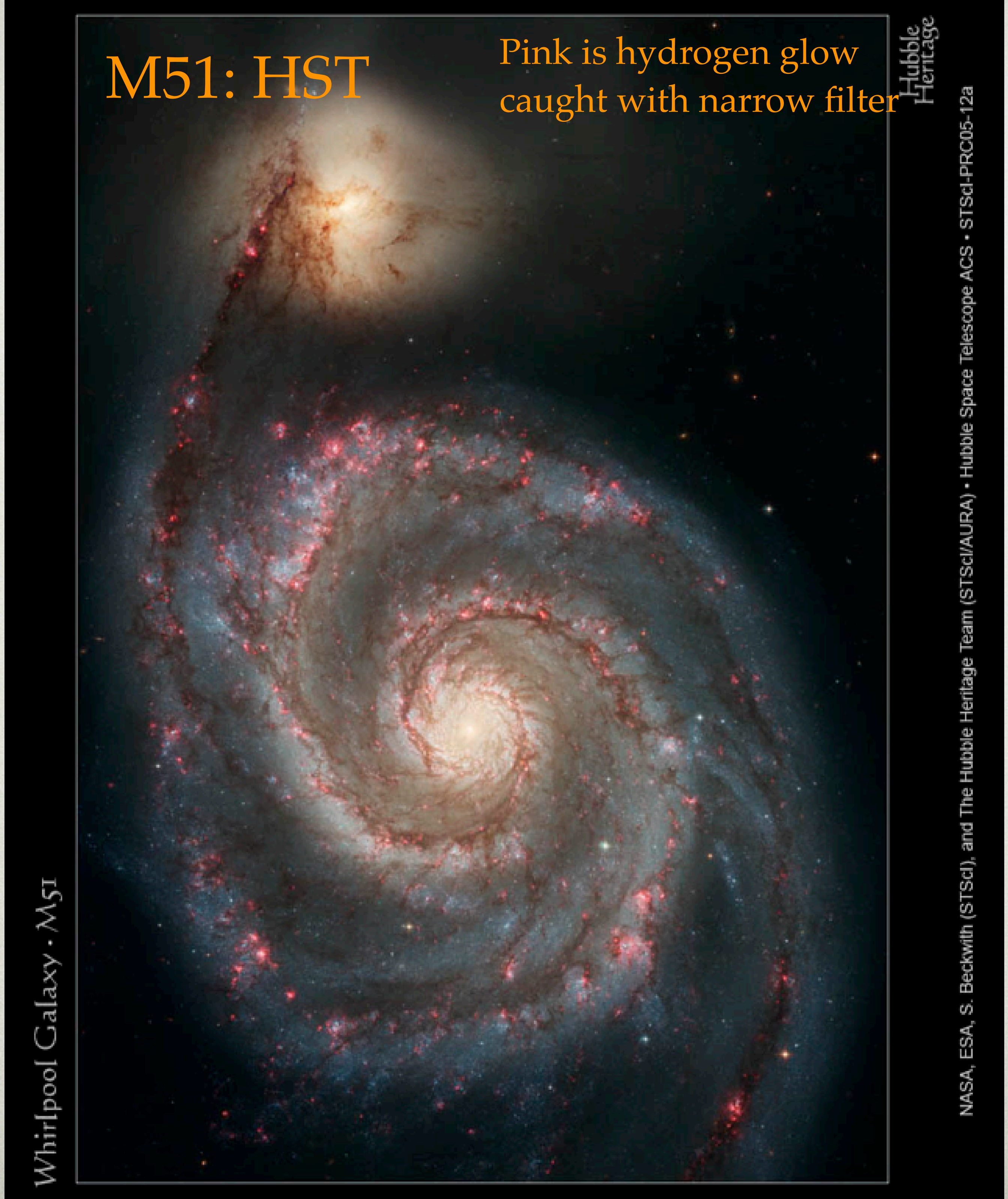
30 CCD, 120 megapixel camera



600 fiber spectrograph

M51: HST

Pink is hydrogen glow caught with narrow filter




M51: SDSS

2Mass Instrumentation

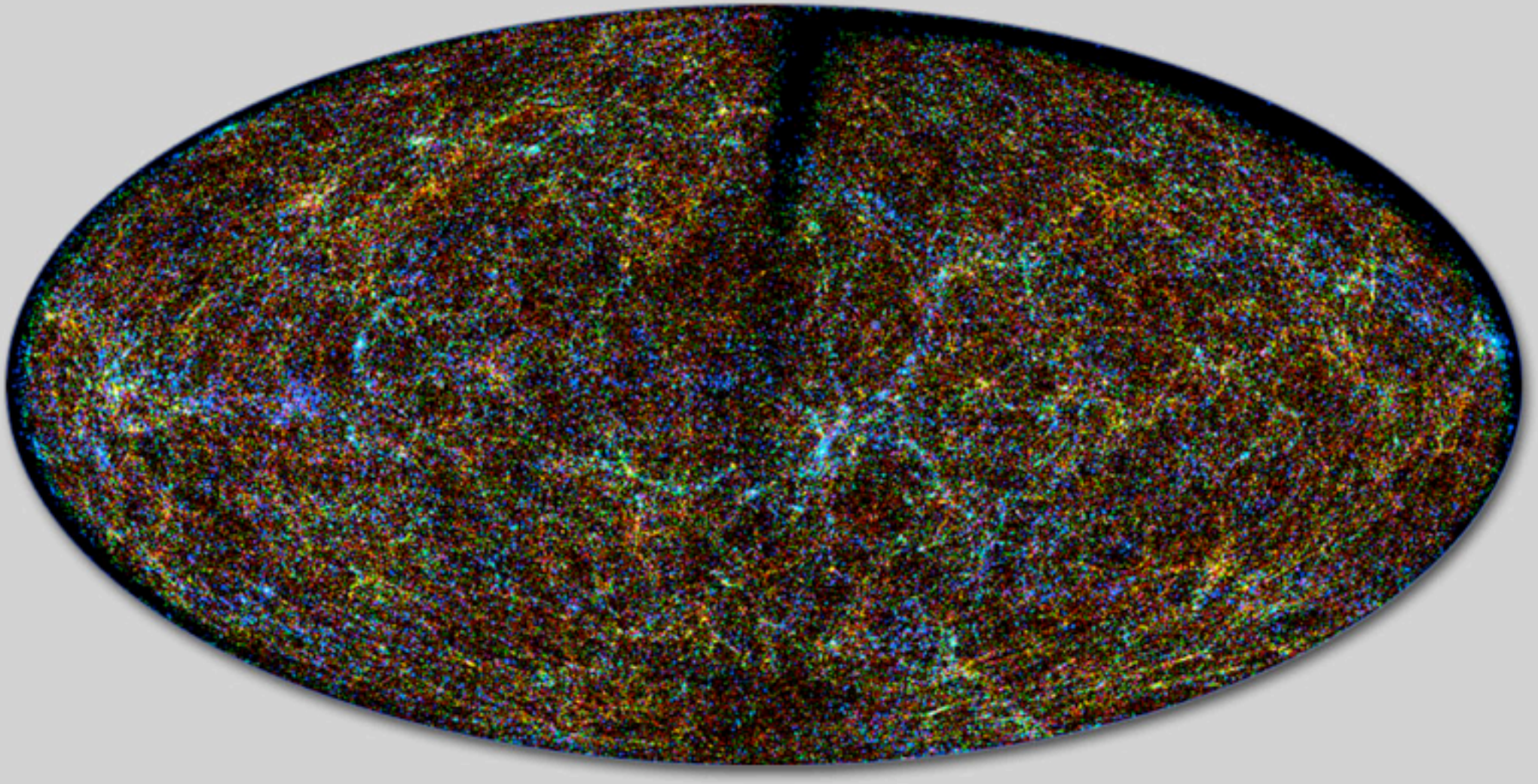
256x256 Infrared Camara

Two dedicated 0.6m telescope

2MASS Showcase

The Infrared Universe Light from 1.6 million galaxies reveals the structure of the local universe

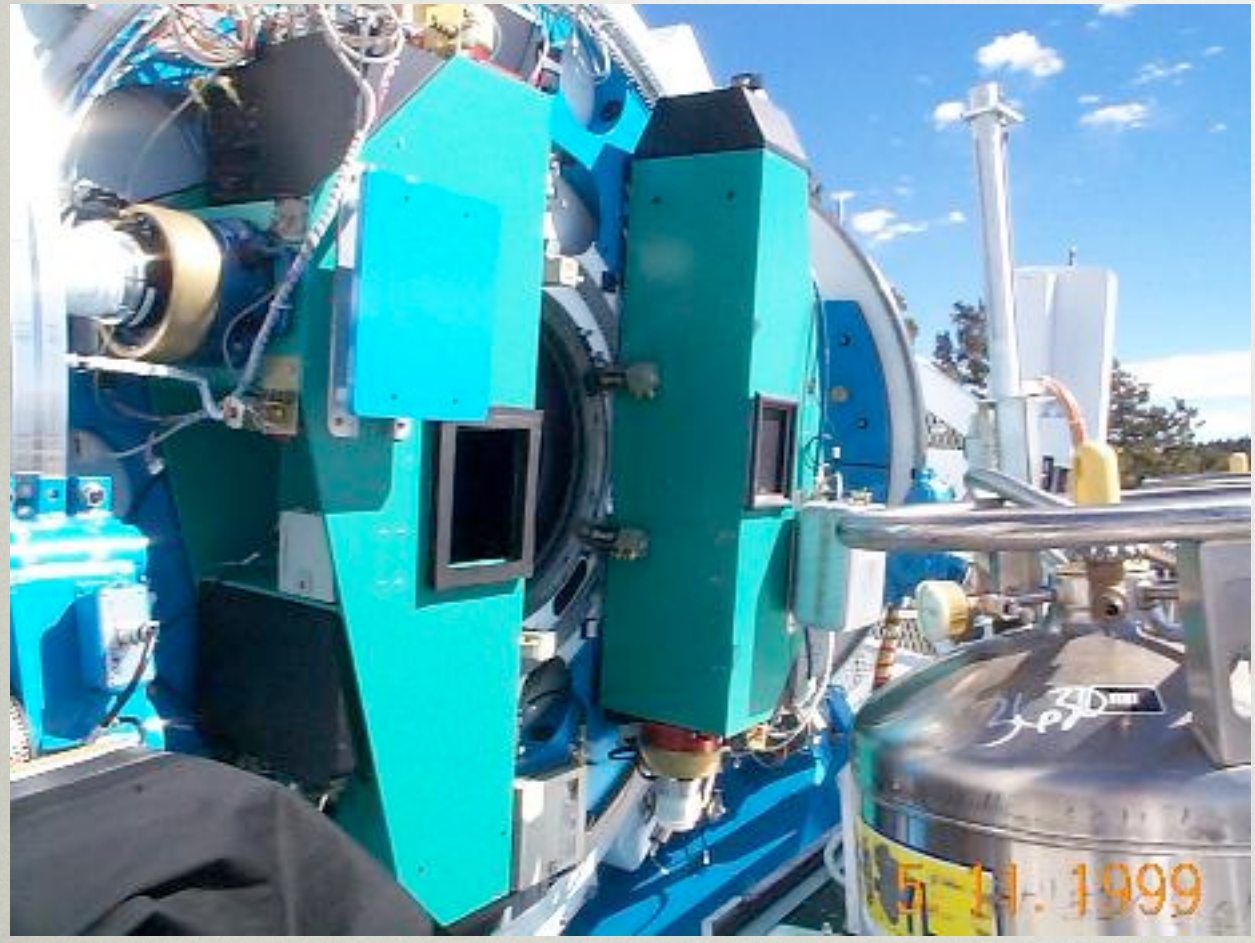
2MASS Showcase

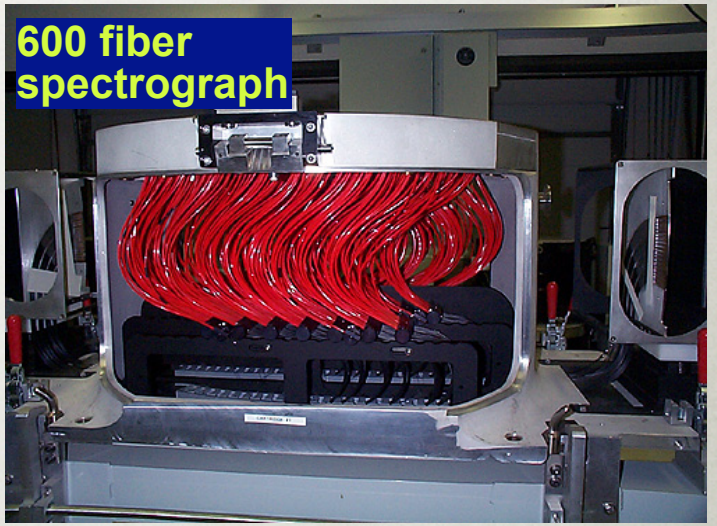


Galaxies of the Infrared Sky Near and far structures in the local universe are color-coded by galaxy brightness

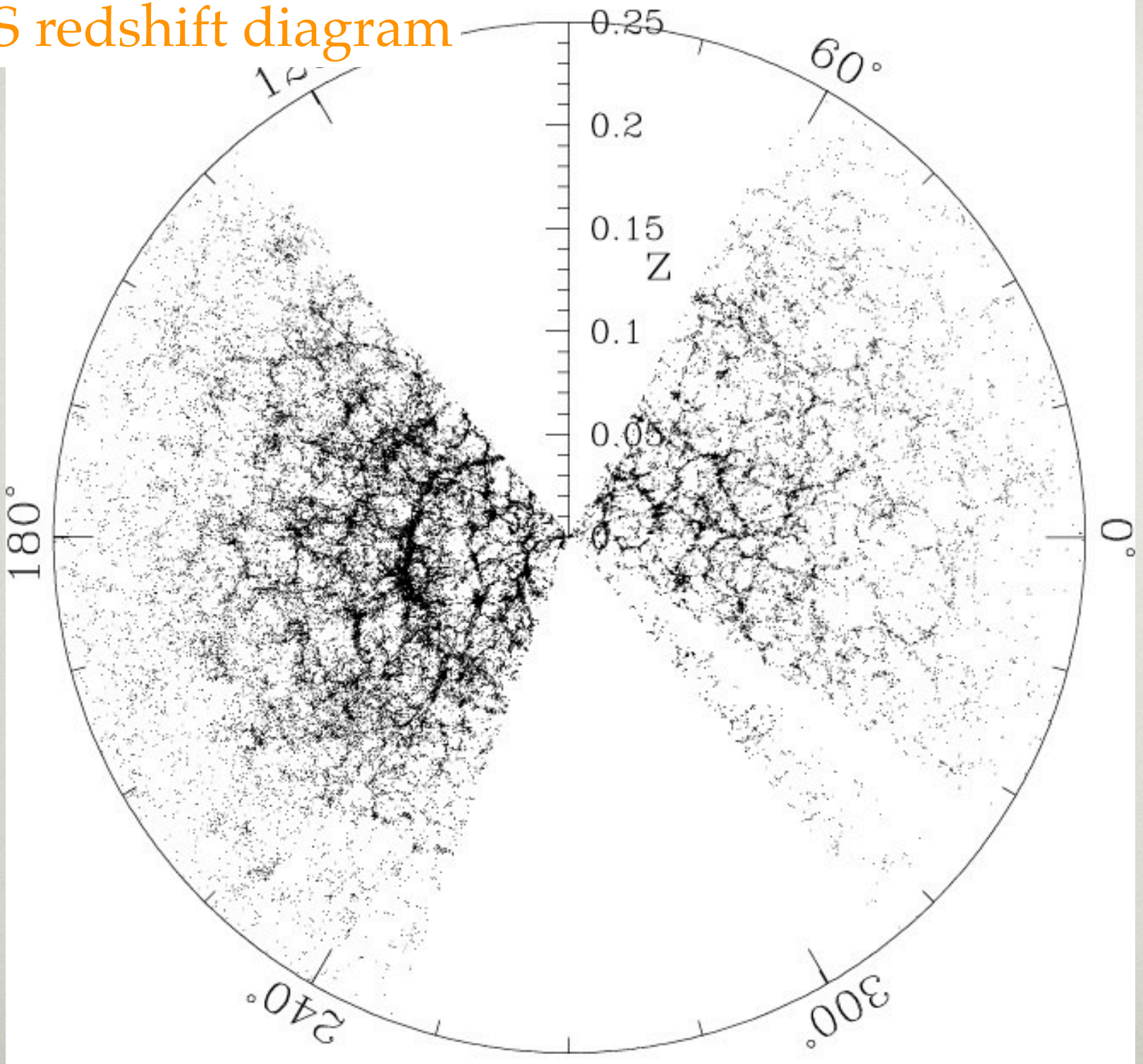
SDSS Spectrographs

SDSS measures precice redshifts for 1 million galaxies

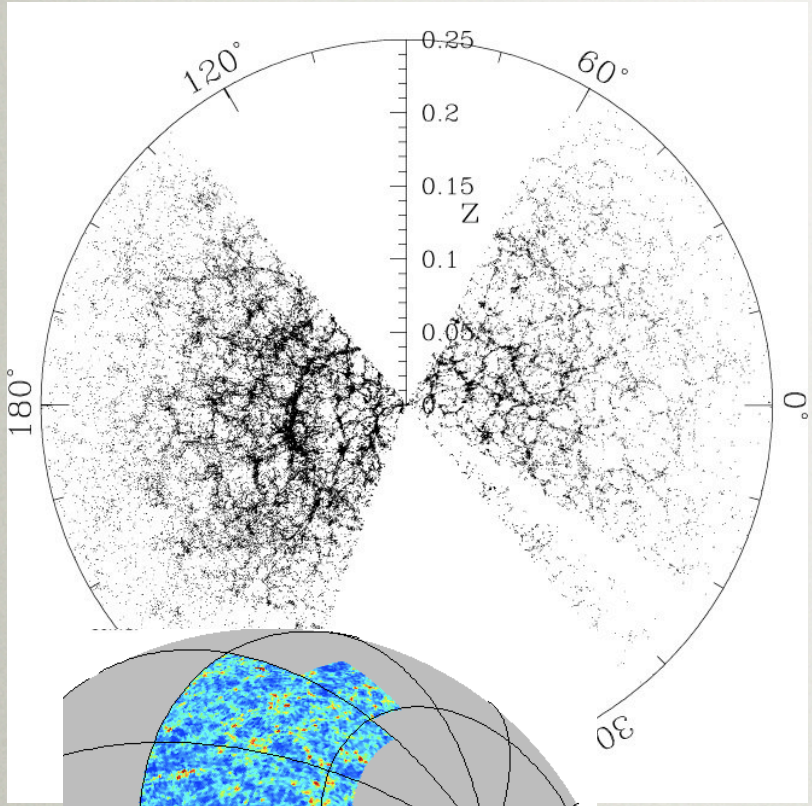


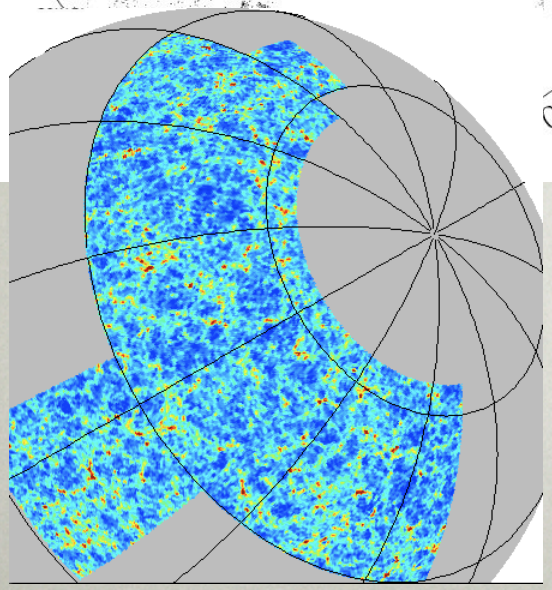


SDSS redshift diagram

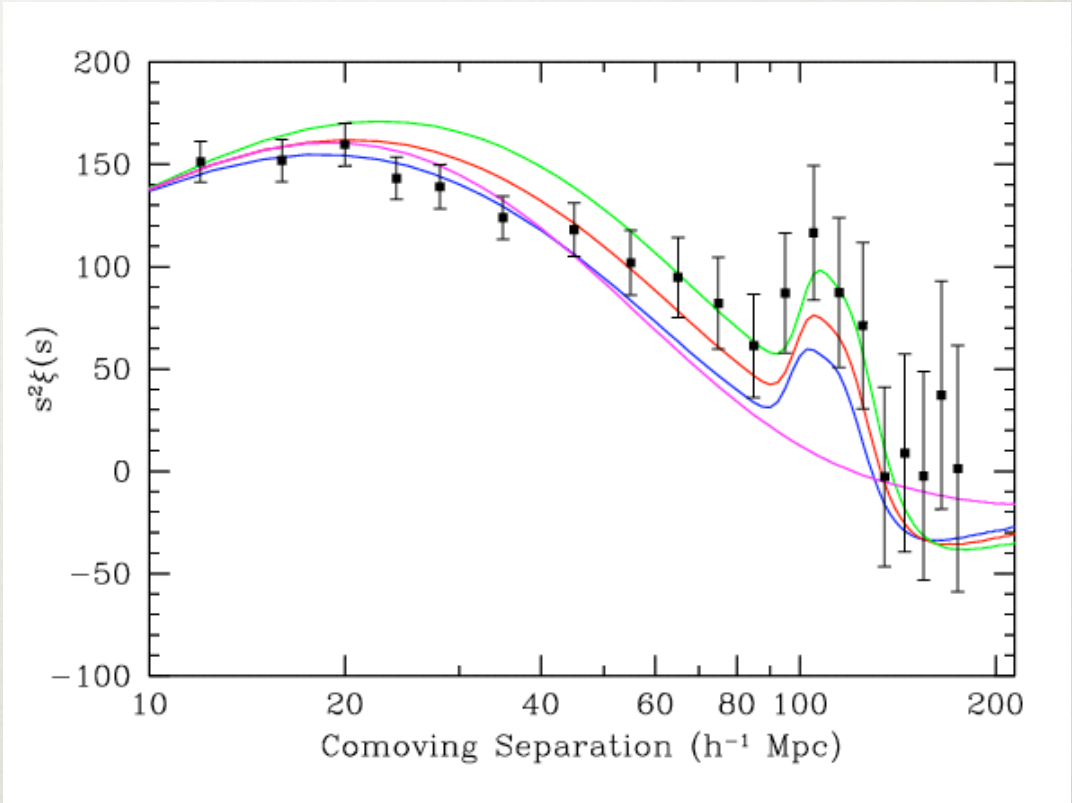


Galaxy Distribution has Features





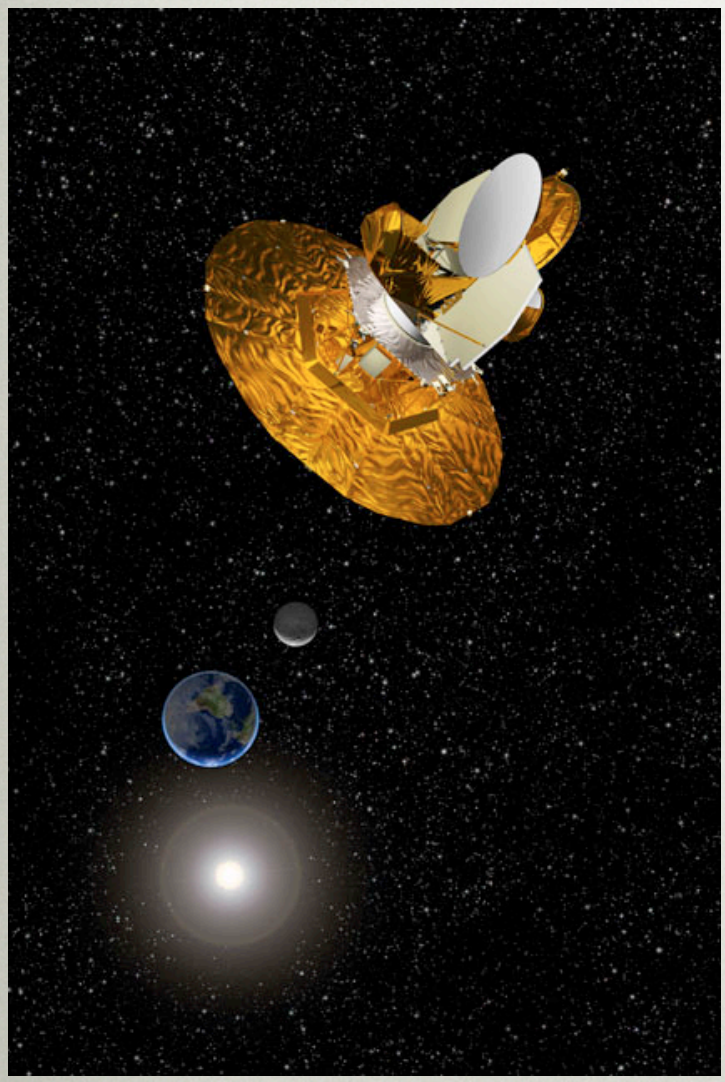
Enrique Gatzanaga

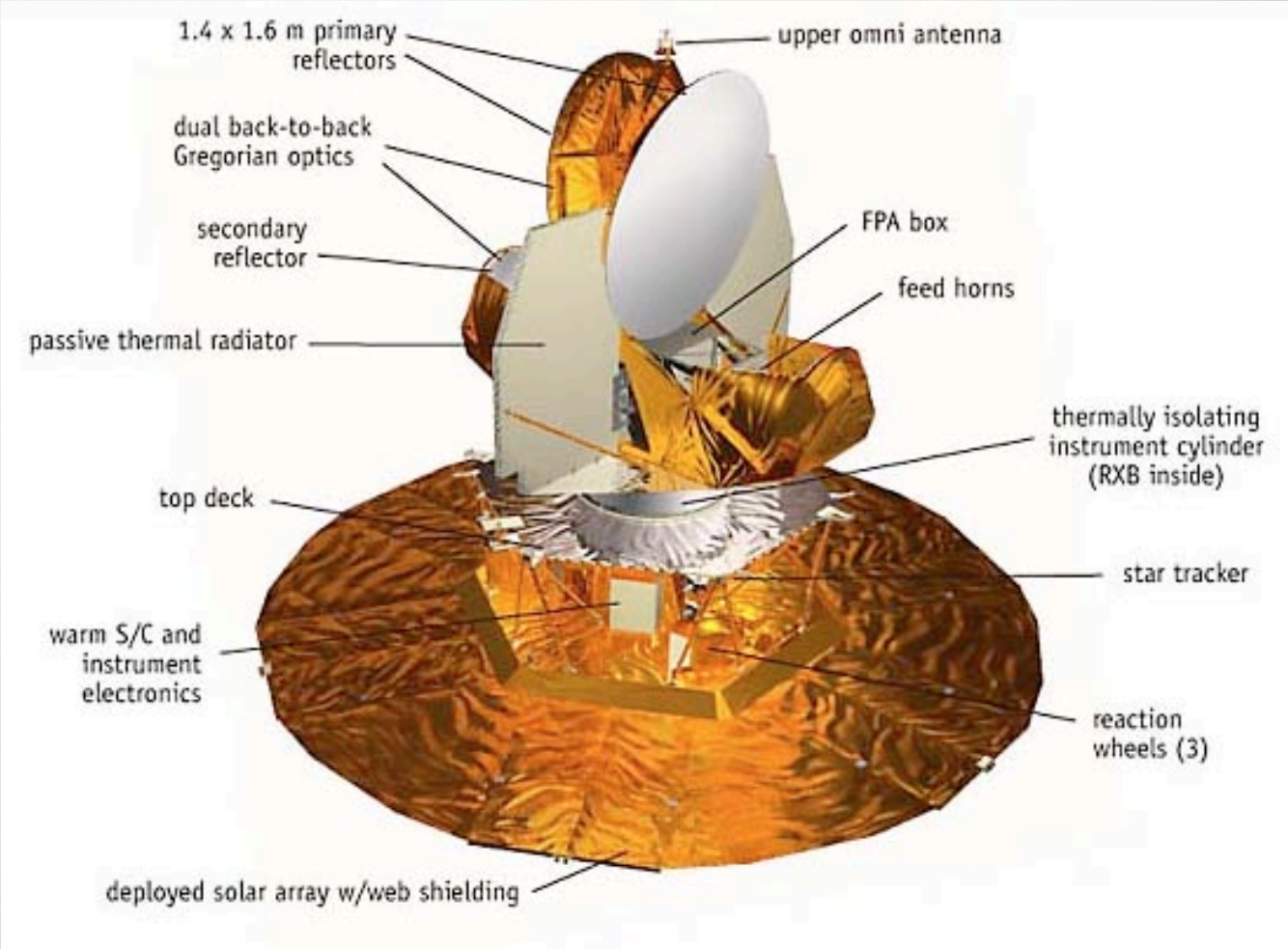


Daniel Eisenstein

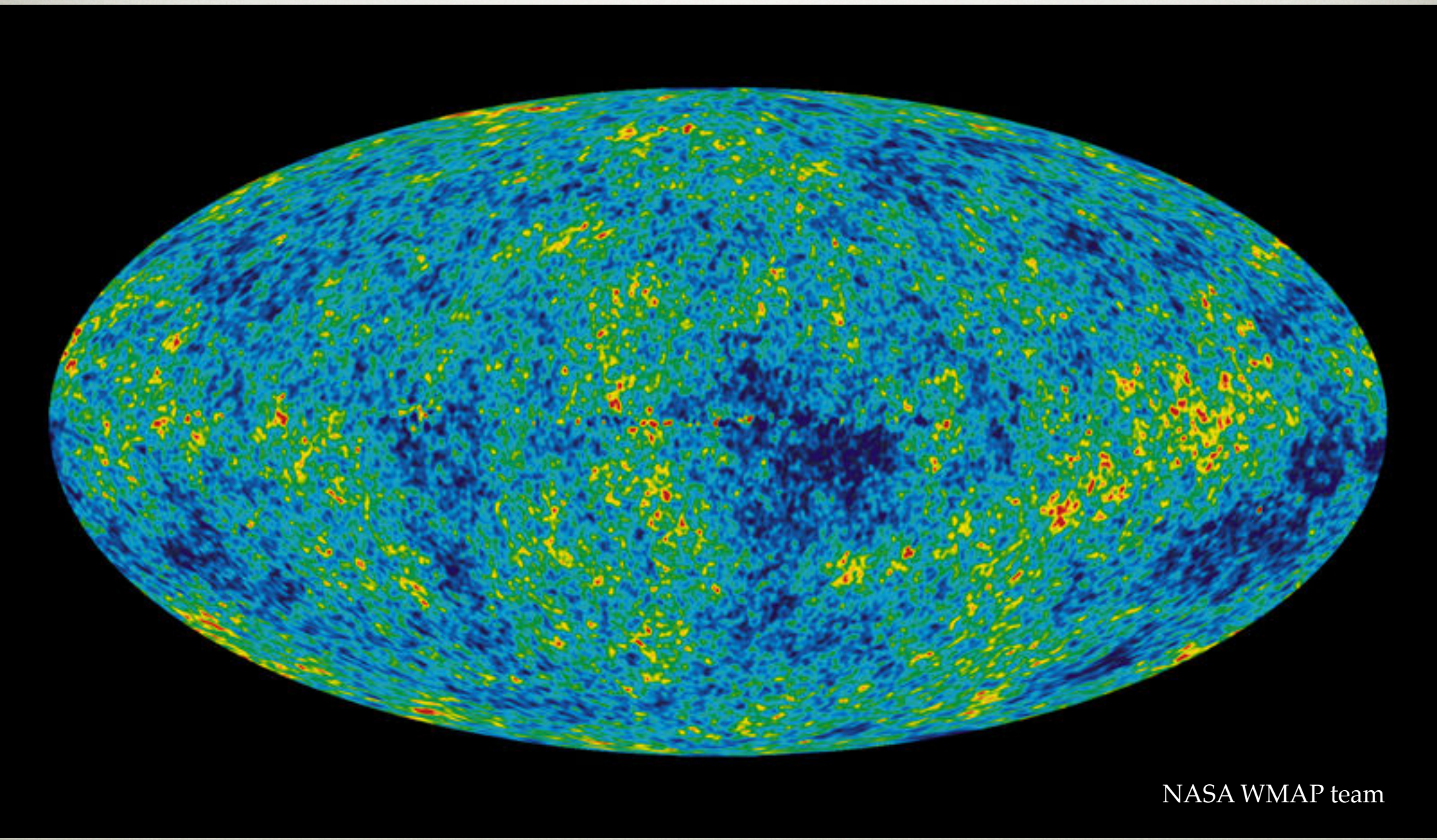
The size of the feature depends on cosmology

Wilkonson Microwave Anisotrpy Probe (WMAP)



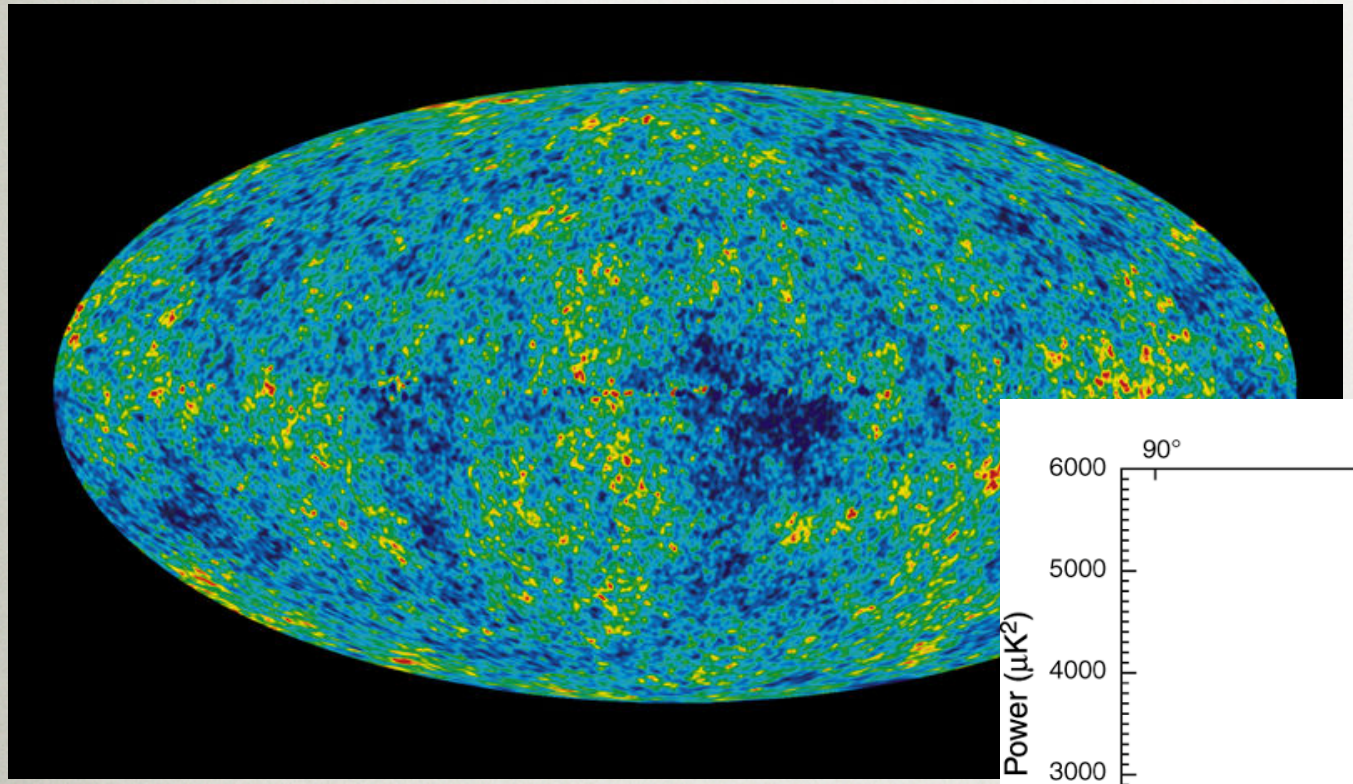


The 3 degree Cosmic Microwave Background

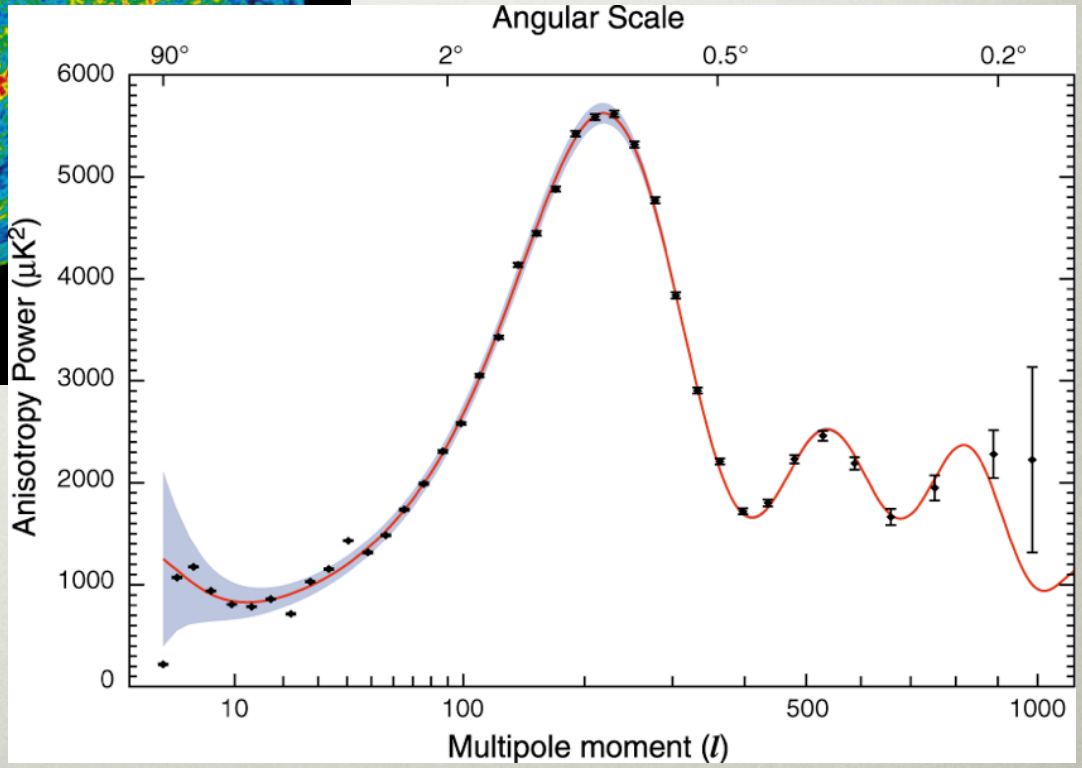


NASA WMAP team

The CMB distribution has features



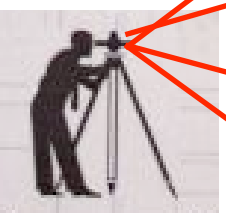
NASA WMAP team



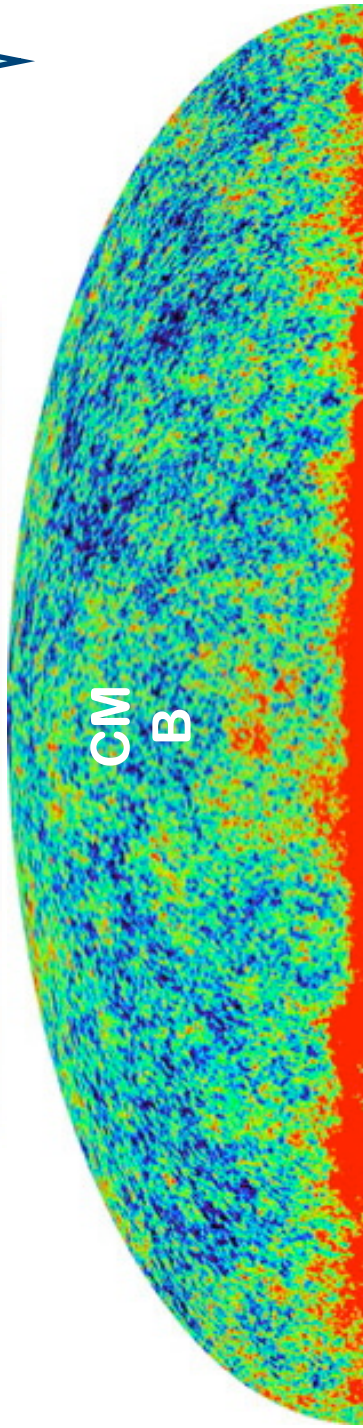
NASA WMAP team

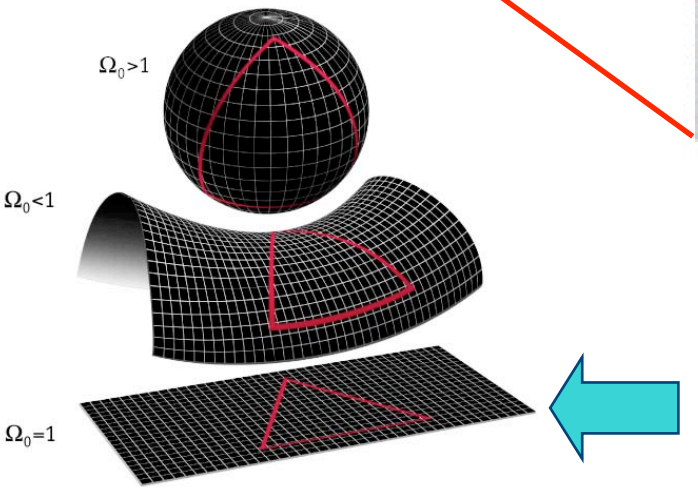
These too depends on cosmology

Looking back in time in the Universe



SDSS GALAXIES



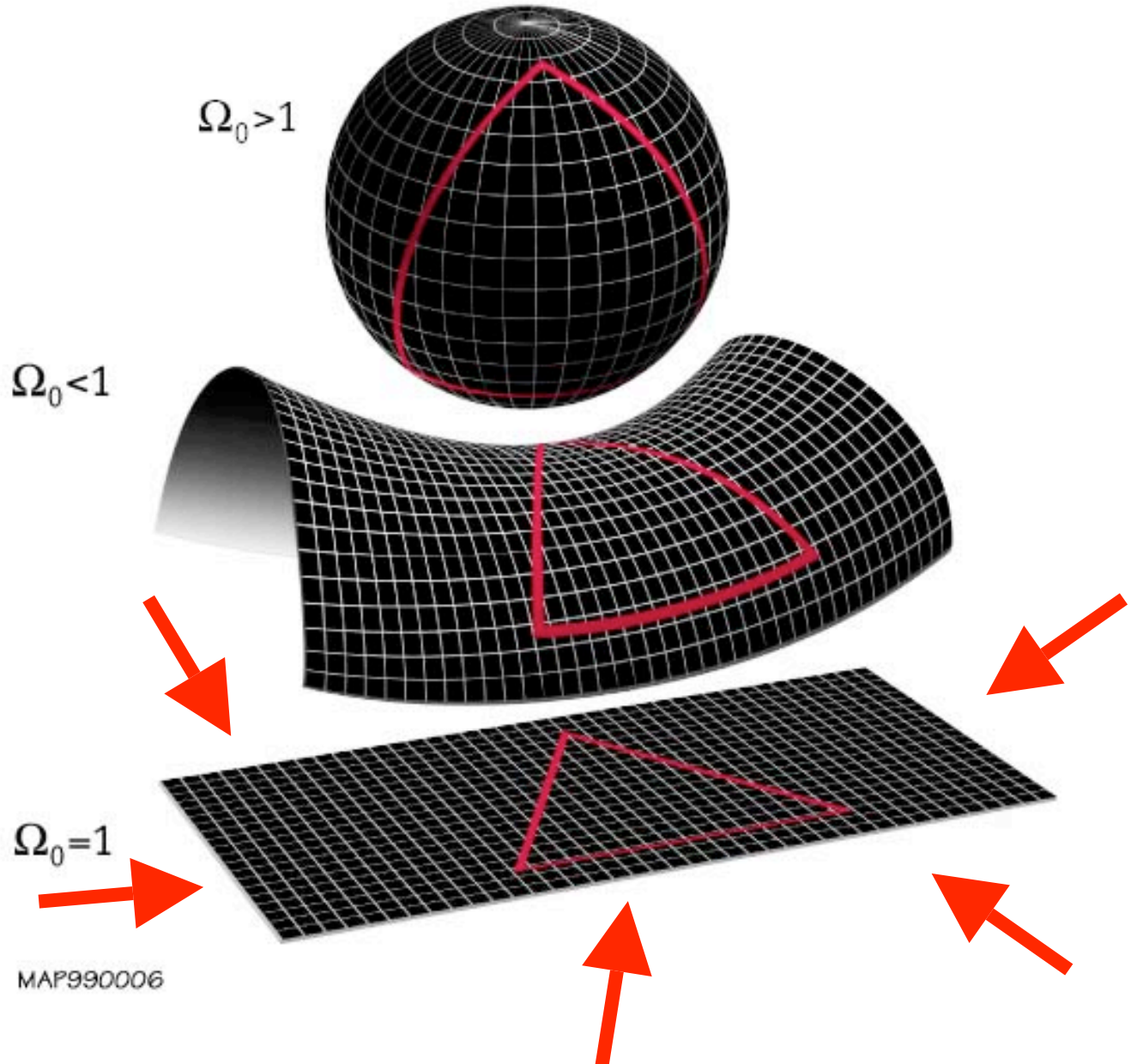


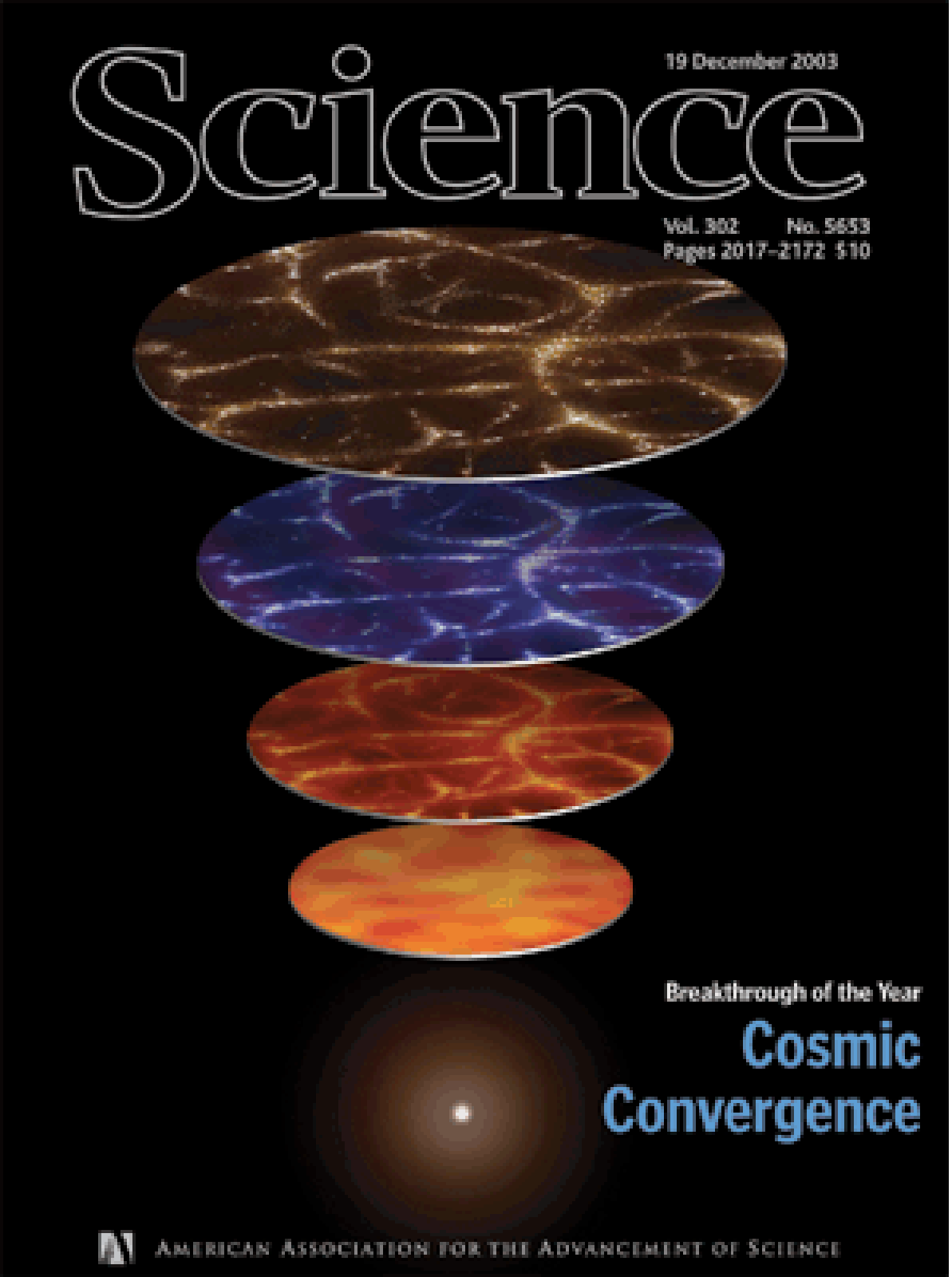
FLAT GEOMETRY

CREDIT: WMAP & SDSS websites

Courtesy: Bob Nichol

UNIVERSE IS FLAT TO 1% PRECISION





"*It is one of the ultimate discoveries in basic science*", said Don Kennedy, editor-in-chief of Science, "*It stirs our imagination even though it challenges our ability to understand*."

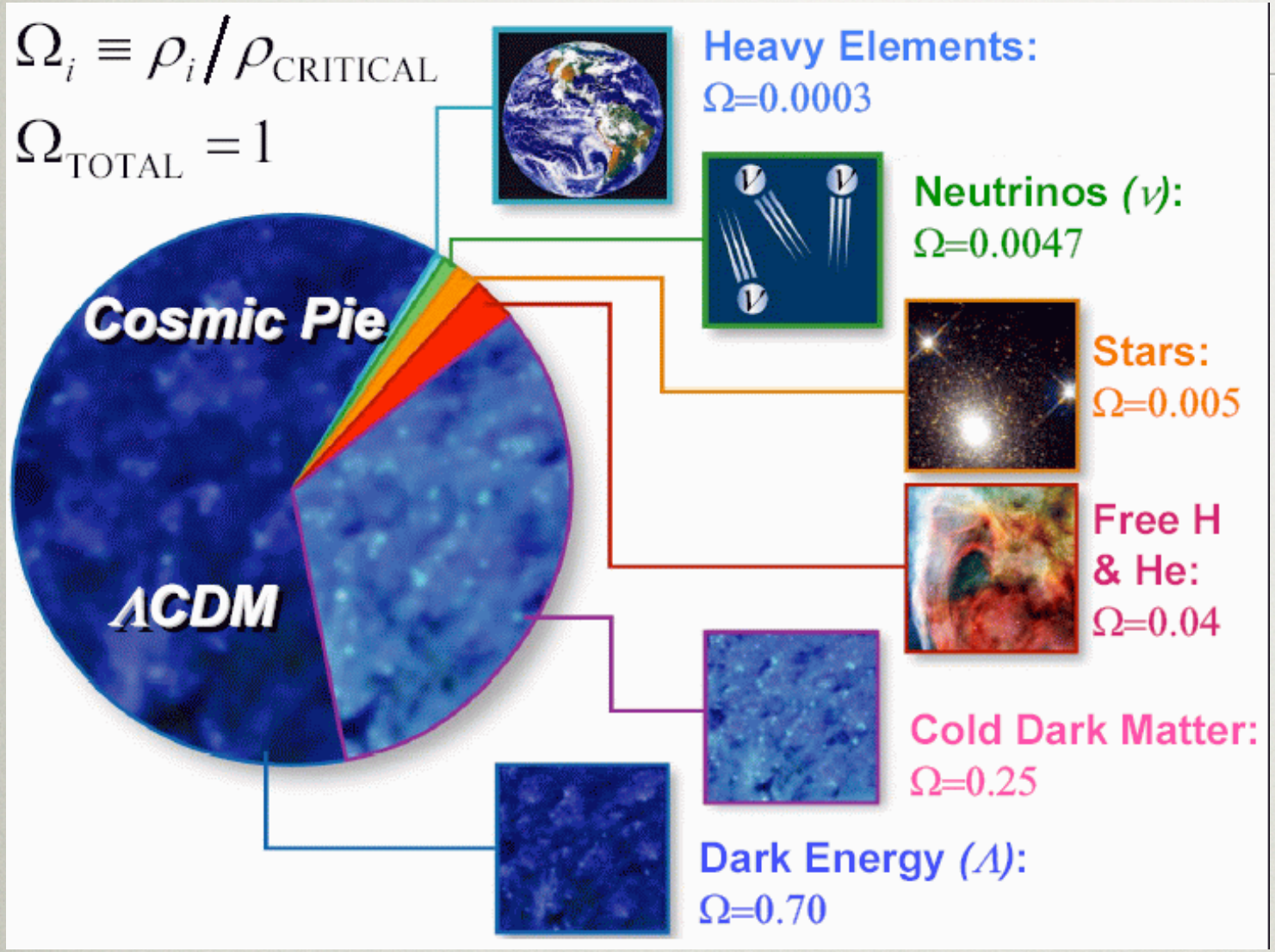
"***No longer are scientists trying to confirm the existence of dark energy. Now they are trying to find out what dark energy is made of, and what it tells us about the birth and evolution of the universe***."

Courtesy: Bob Nichol

Dark Energy

The Rise of Statistical Cosmology

The New Census of the Universe



95% of the Universe is in Dark Energy and Dark matter.

We understand neither.

The confirmation of Dark Energy points to a major hole in our understanding of fundamental physics

DARK ENERGY

1. The Cosmological Constant Problem

   Particle physics theory currently provides no understanding of why the vacuum energy density is so small:

   $$\rho_{DE}^{(Theory)} / \rho_{DE}^{(obs)} = 10^{120}$$

2. The Cosmic Coincidence Problem

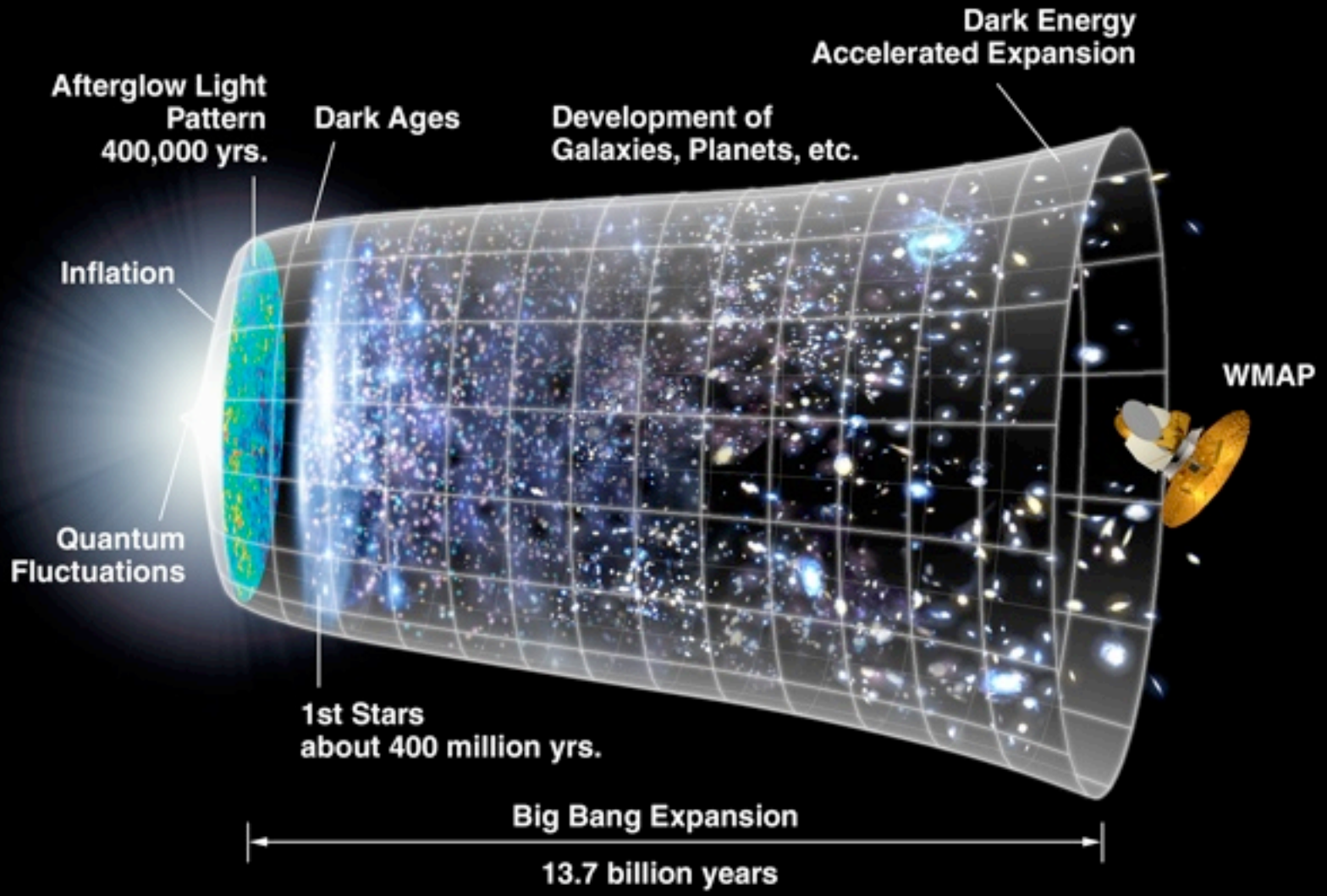
   Theory provides no understanding of why the Dark Energy density is just now comparable to the matter density.

3. What is it?

   Is dark energy the vacuum energy? a new, ultra-light particle? a breakdown of General Relativity on large scales? Evidence for extra dimensions?

The nature of the Dark Energy is one of the outstanding unsolved problems of fundamental physics.

This is an observational driven field.




Dark Energy
What is it?
The cosmological constant?
A new particle / field?
A modification of general relativity?

Measuring Dark Energy

- One measures dark energy through how it affects the universe expansion rate, H(z):

$$H^2(z) = H^2_0 \left[\Omega_M (1+z)^3 + \Omega_R (1+z)^4 + \Omega_{DE} (1+z)^{3(1+w)} \right]$$

matter radiation dark energy

- Note **w**, the parameter which describes the evolution of the density of dark energy with redshift. A cosmological constant has **w = –1.**

w is currently constrained to ~20% by WMAP, SDSS, and supernovae

- Measurements are usually integrals over H(z) $r(z) = \int dz / H(z)$
- Standard Candles (e.g., supernova) measure $d_L(z) = (1+z)\, r(z)$
- Standard Rulers measure $d_a(z) = (1+z)^{-1}\, r(z)$
- Volume Markers measure $dV/dz d\Omega = r^2(z)/H(z)$
- The rate of growth of structure is a more complicated function of H(z)

The Race to Measure Dark Energy

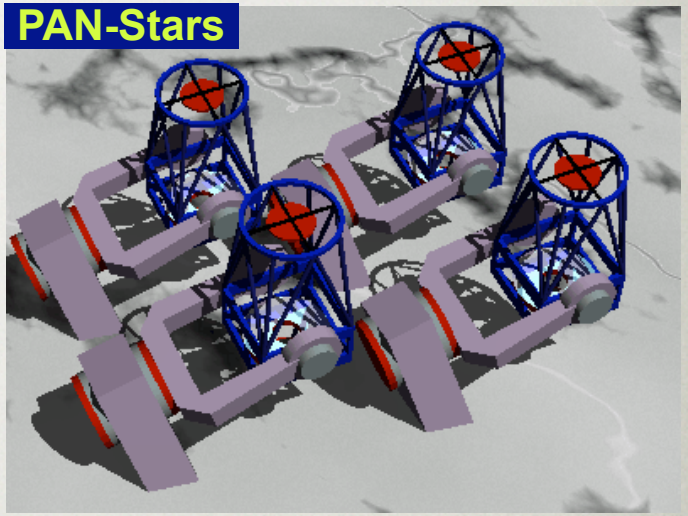
And The Dark Energy Survey

The Large Survey Telescope

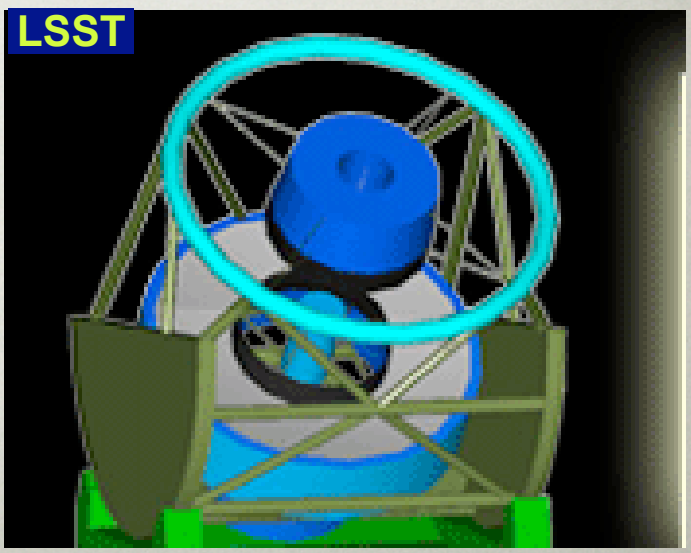
- PAN-Stars
  - 2006- one telescope
  - 1.5m telescope
  - 7 sq-degree camera
  - Private observatory model:
    - Air Force funds University of Hawaii
- LSST
  - 2012
  - 8m (6.5m collecting)
  - 7 sq-degree camera
  - Collaboration model:
    - Universities, NSF, DOE, private donors
- Both are multipurpose machines: killer asteroid searches, time domain, etc

Two candidates for the LST:

PAN-Stars



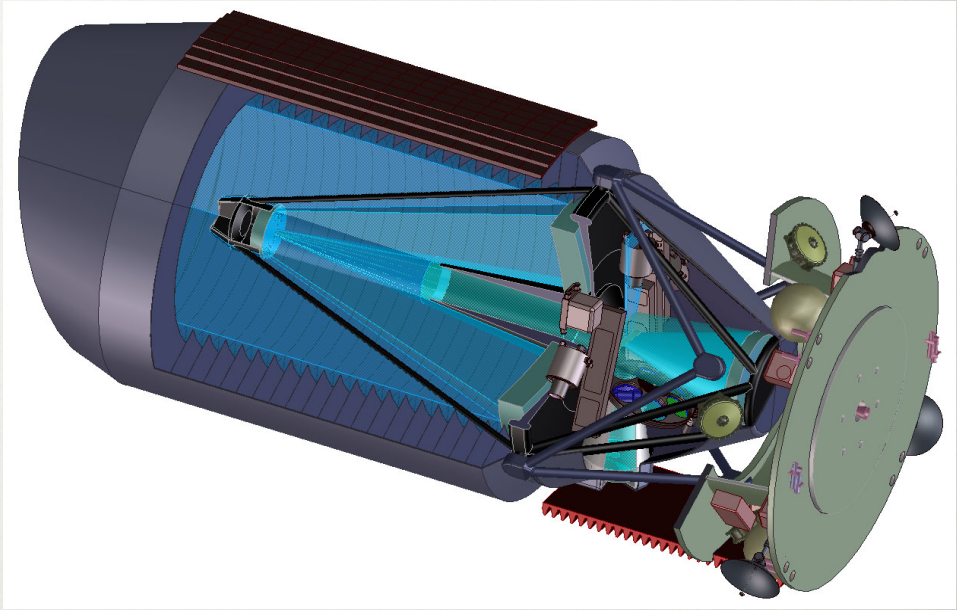
LSST

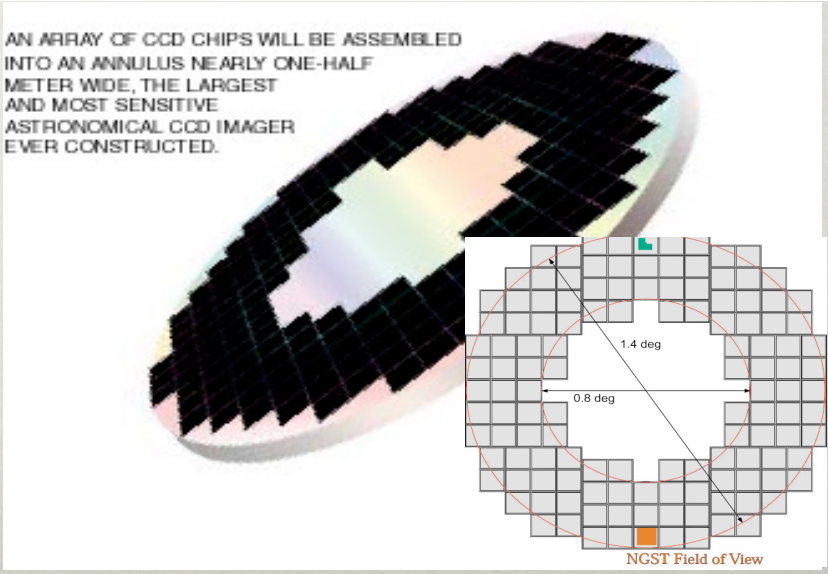


Super Nova Acceleration Probe

A dedicated experiment to study dark energy

- Dedicated instrument, few moving parts
- Mirror: 2 meter aperture sensitive to light from distant SN
- Large Field of View: to see lots of SNe, has half-billion pixel mosaic camera (~100x larger Field than Hubble)
- Collaboration model: DOE/ Universities and NASA

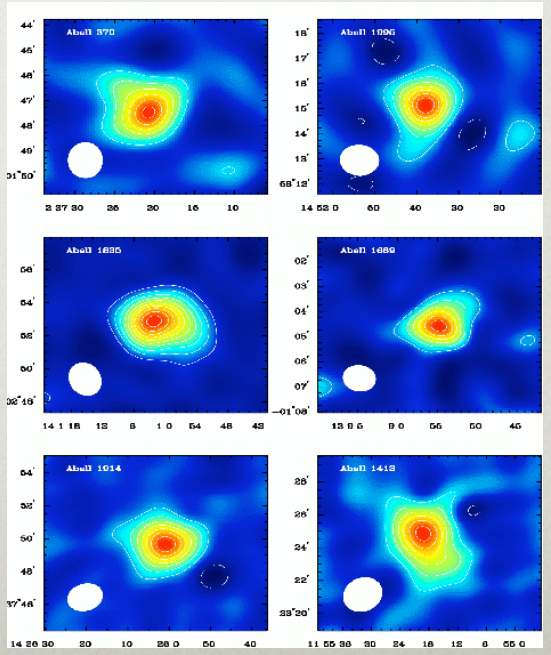




Intermediate Time Scale
South Pole Telescope SZ Survey

- 10m submillimeter telescope
  - At the South Pole
  - 1000 element bolometer array
  - 1.25 arcminute resolution
- Collaboration
  - John Carlstrom (Chicago) PI
  - Chicago, CWRU, Berkeley, Illinois and Harvard-Smithsonian CfA
- Science Goals
  - 4000 sq-degree Sunyaev-Zeldovich effect survey
  - Cluster abundances and spatial power spectra
  - CMB polarization
- NSF funded, Survey slated for 2007

SPT site

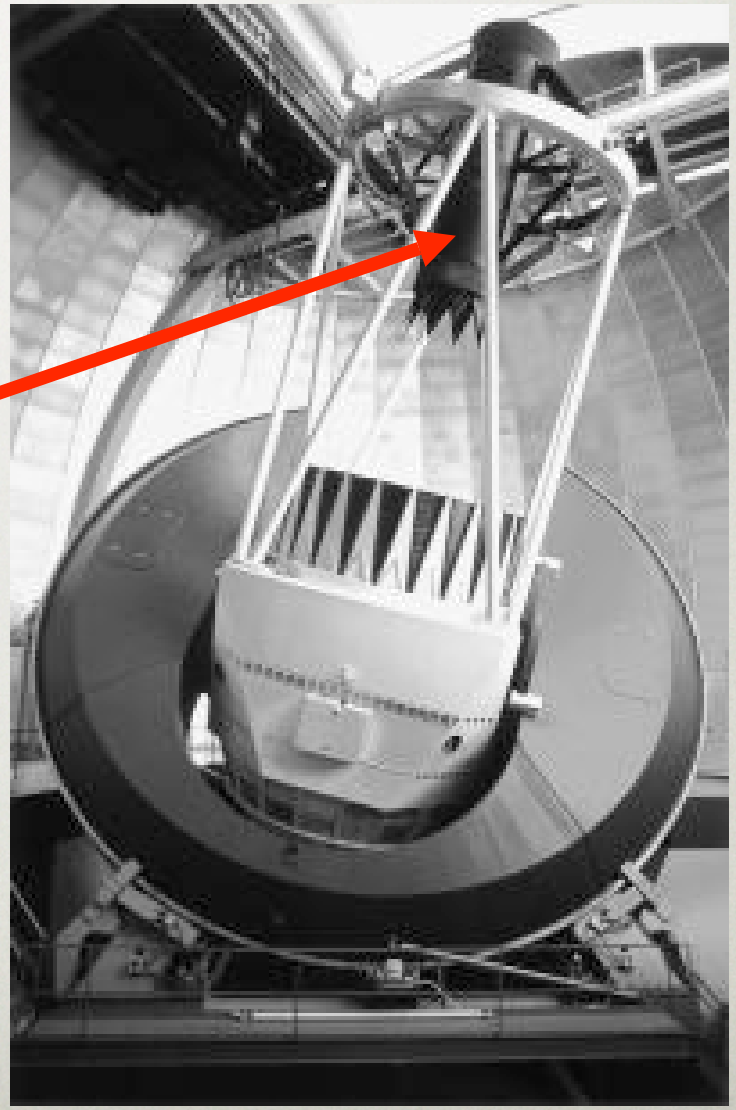


SZ observations of clusters

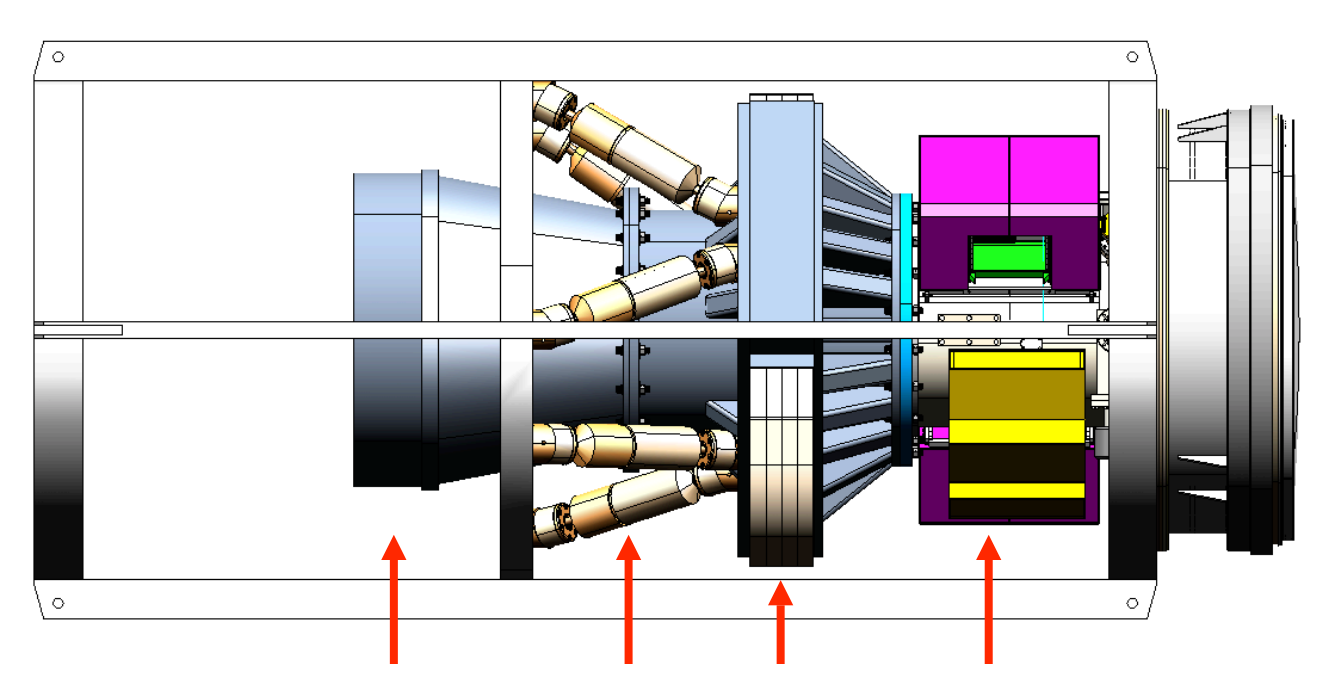
But, No redshifts!

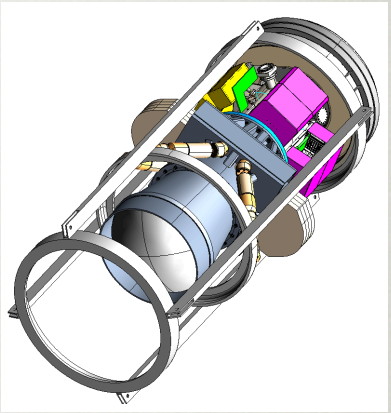
THE DARK ENERGY SURVEY

- **Science Goals:**
  - Perform a 5000 sq. deg. survey of the southern galactic cap
  - Map the cosmological density field to z=1
  - constrain the Dark Energy parameter w to ~ 5% with 4 complementary techniques
  - begin to constrain dw/dz
- **New Equipment:**
  - Replace the PF cage on the CTIO Blanco 4m telescope with a new 2.2 deg. FOV optical CCD camera
- **Time scale:**
  - Instrument Construction 2005-2009
- **Survey:**
  - 30% of the telescope time from 2009-2013



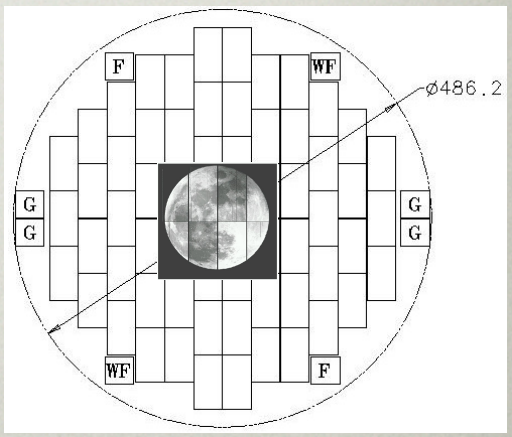
DECam



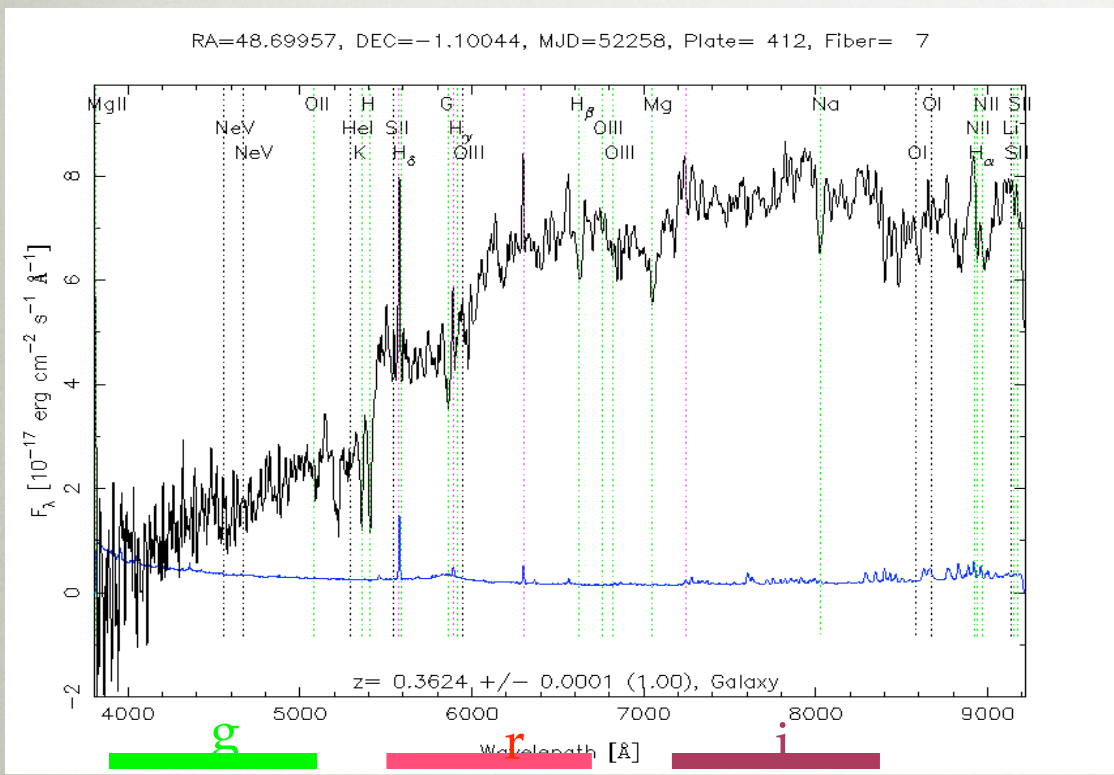


- 5 element optical corrector
- Hexapod for focus, xy translation
- 0.6m filters: g,r,i,z
- Very large focal plane
- Readout: 17s readout time, 10 e- noise

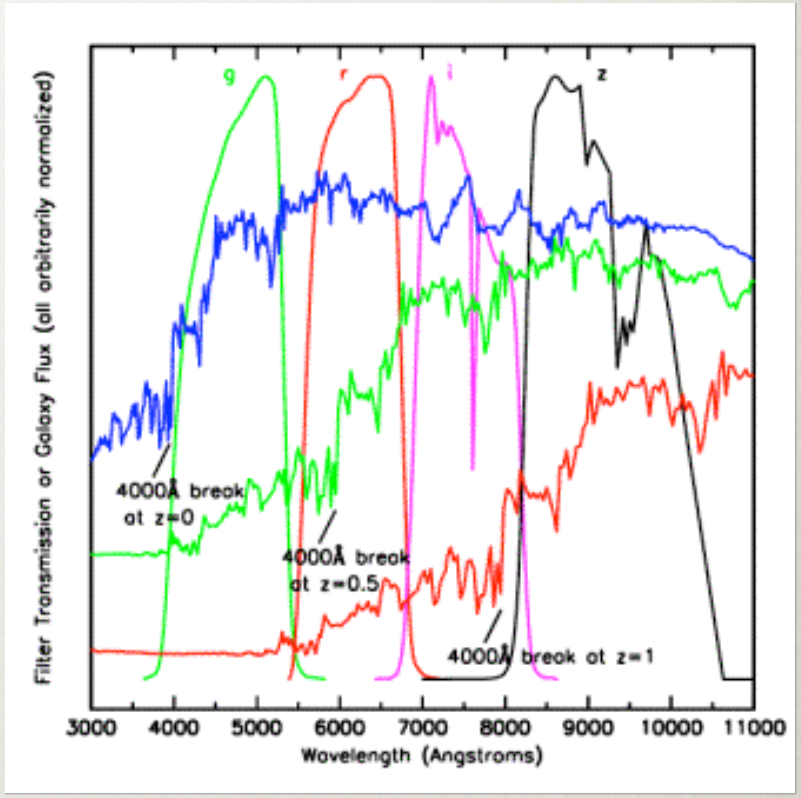
Focal plane:
62 2kx4k Image CCDs:
520 MPix
8 2kx2k Guide, focus, alignment



Photometric Redshifts



E galaxy spectra



Redshift

Photometric redshifts are the key technology of the Dark Energy Survey. With them, we can pursue 4 key projects of extraordinary power.

DES 4 Key Projects

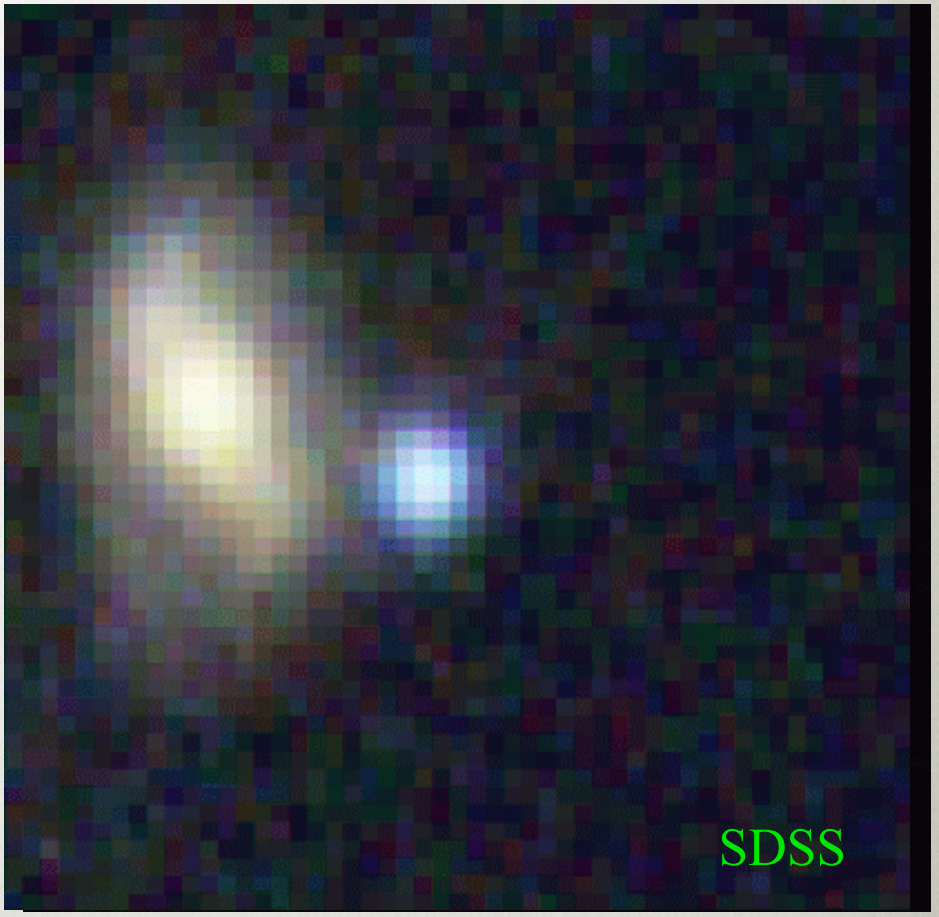
- Dark Energy using the "gold standard" probe
  - Type 1a Supernovae distances
    - 2000 supernovae

- Dark Energy using new probes
  - Galaxy Cluster counting
    - 20,000 clusters to z=1 with $M > 2x10^{14}\ M_{\odot}$
  - Weak lensing
    - 300 million galaxies with shape measurements
  - Spatial clustering of galaxies
    - 300 million galaxies

I. Supernovae

- Geometric Probe of Dark Energy

- Repeat observations of 40 deg^2, using 10% of survey time
- ~1900 well-measured SN Ia lightcurves, $0.25 < z < 0.75$
- Larger sample, improved *z*-band response compared to ESSENCE, SNLS; address issues they raise
- Improved photometric precision via in-situ photometric response measurements



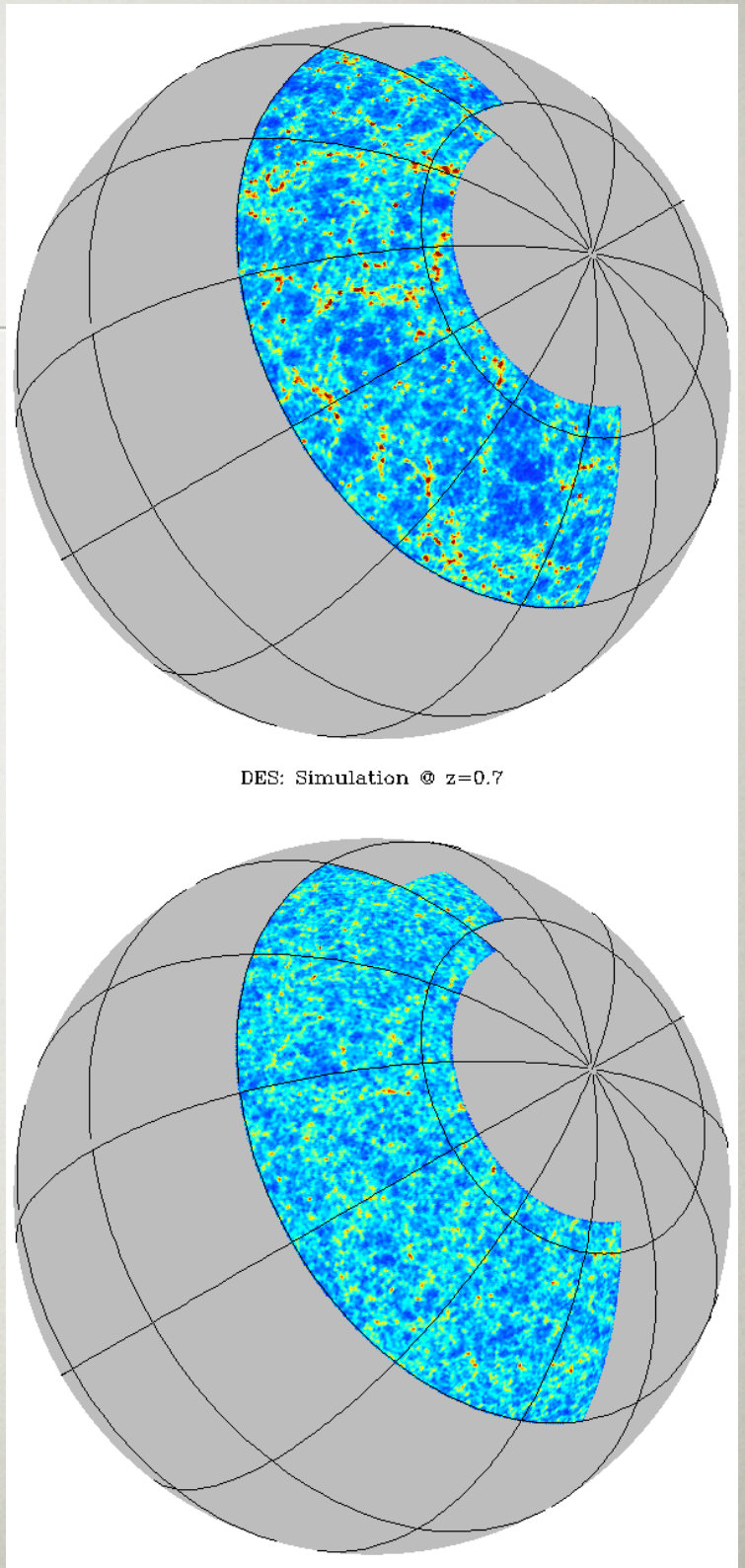
II. Galaxy distribution

z=0.1

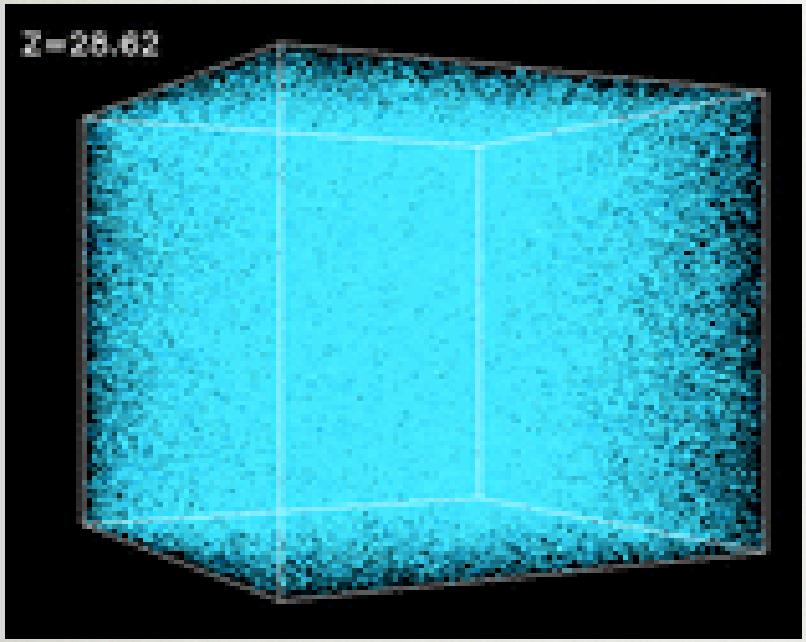
- Geometric Probe of Dark Energy

z=0.7

- 5000 sq-degrees
- 300 million galaxies with photo-z's
- Redshift bins out to z=1.0

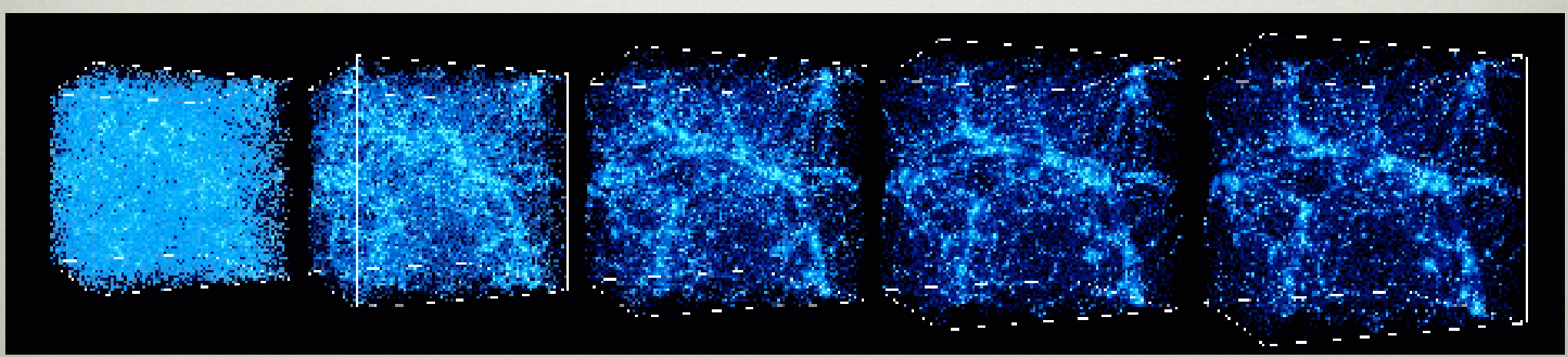


New Probes of Dark Energy

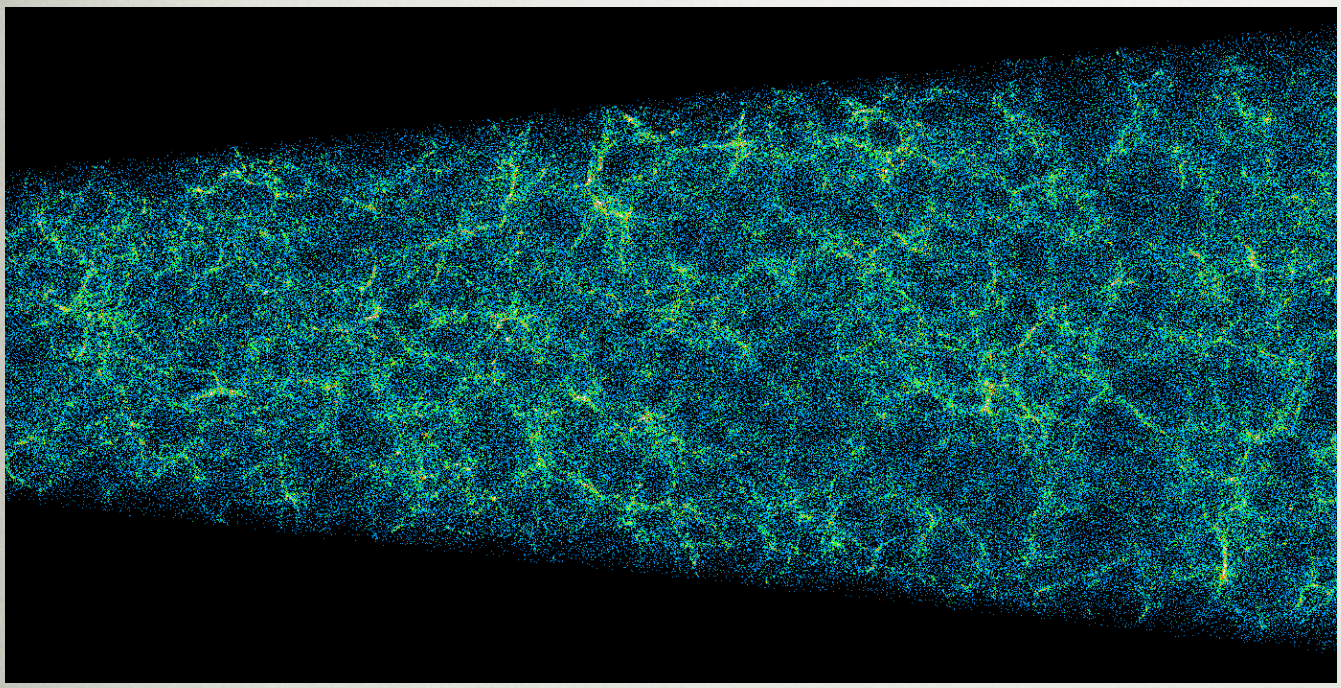


The new probes rely on mapping the cosmological density field.

$z = 30$ $z = 0$

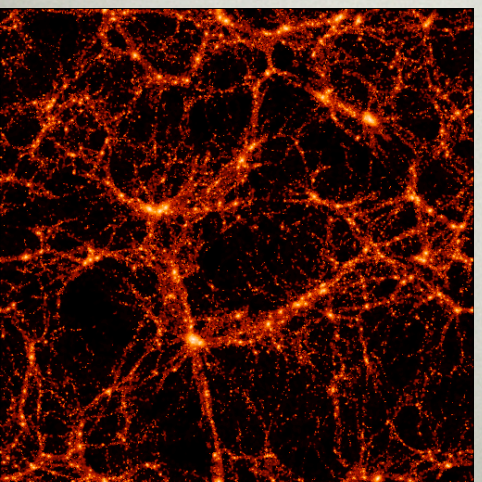


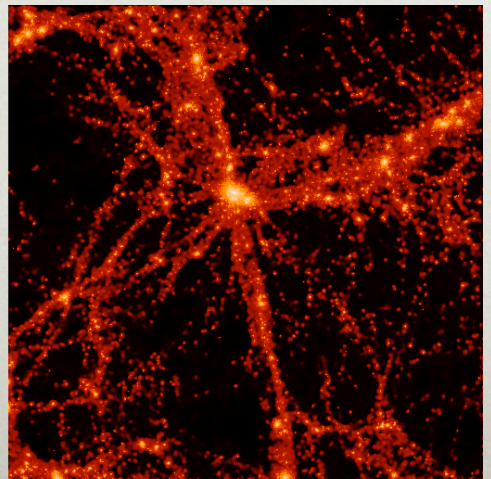
Peaks in the Density Field



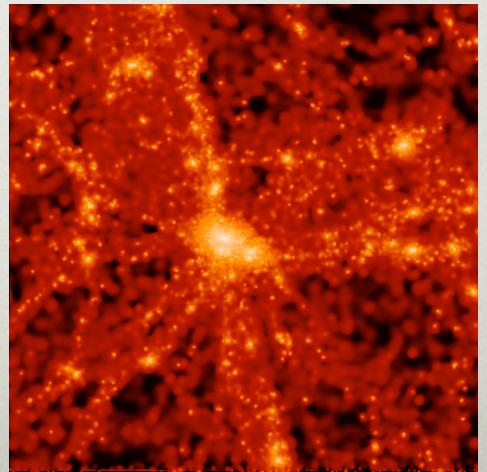
- Clusters of galaxies are peaks of the density field.
- Dark energy influences the number and distribution of clusters and how they evolve with time.

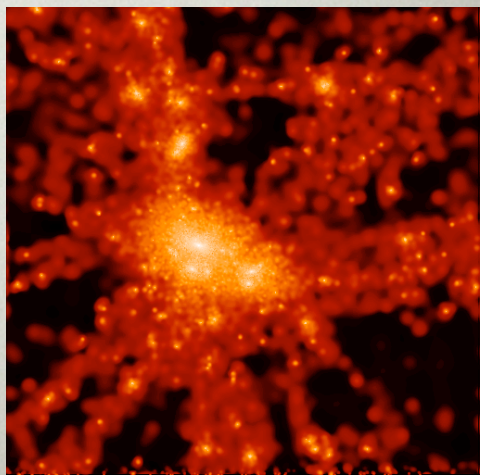
16 Mpc





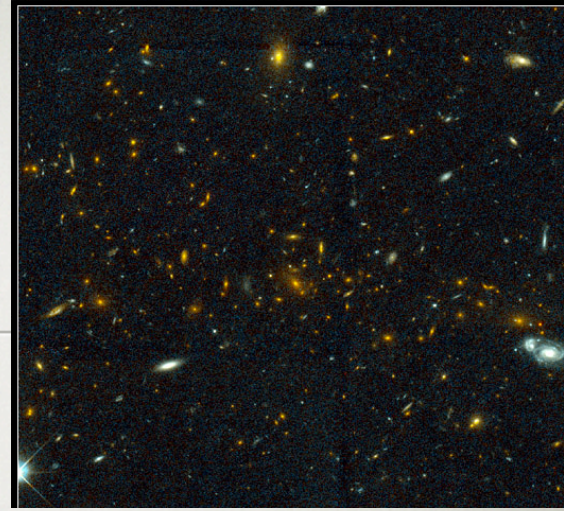
2 Mpc

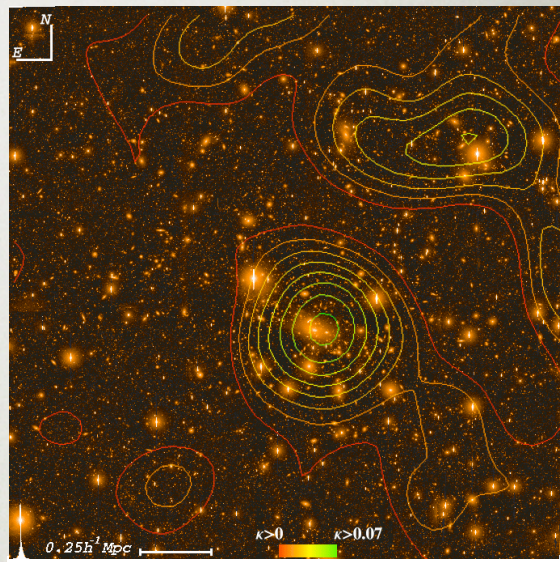


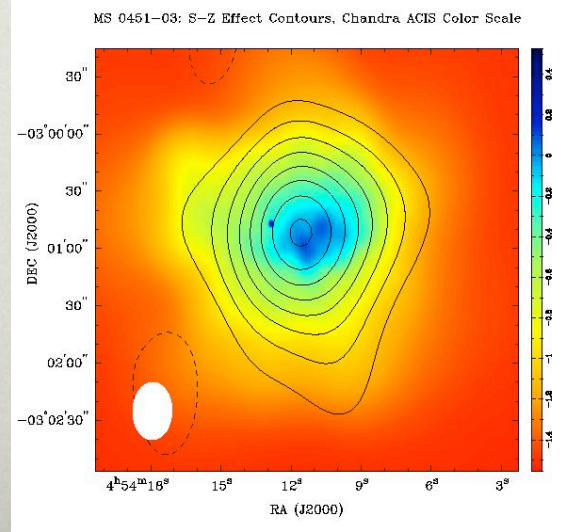


III. Cluster Counting

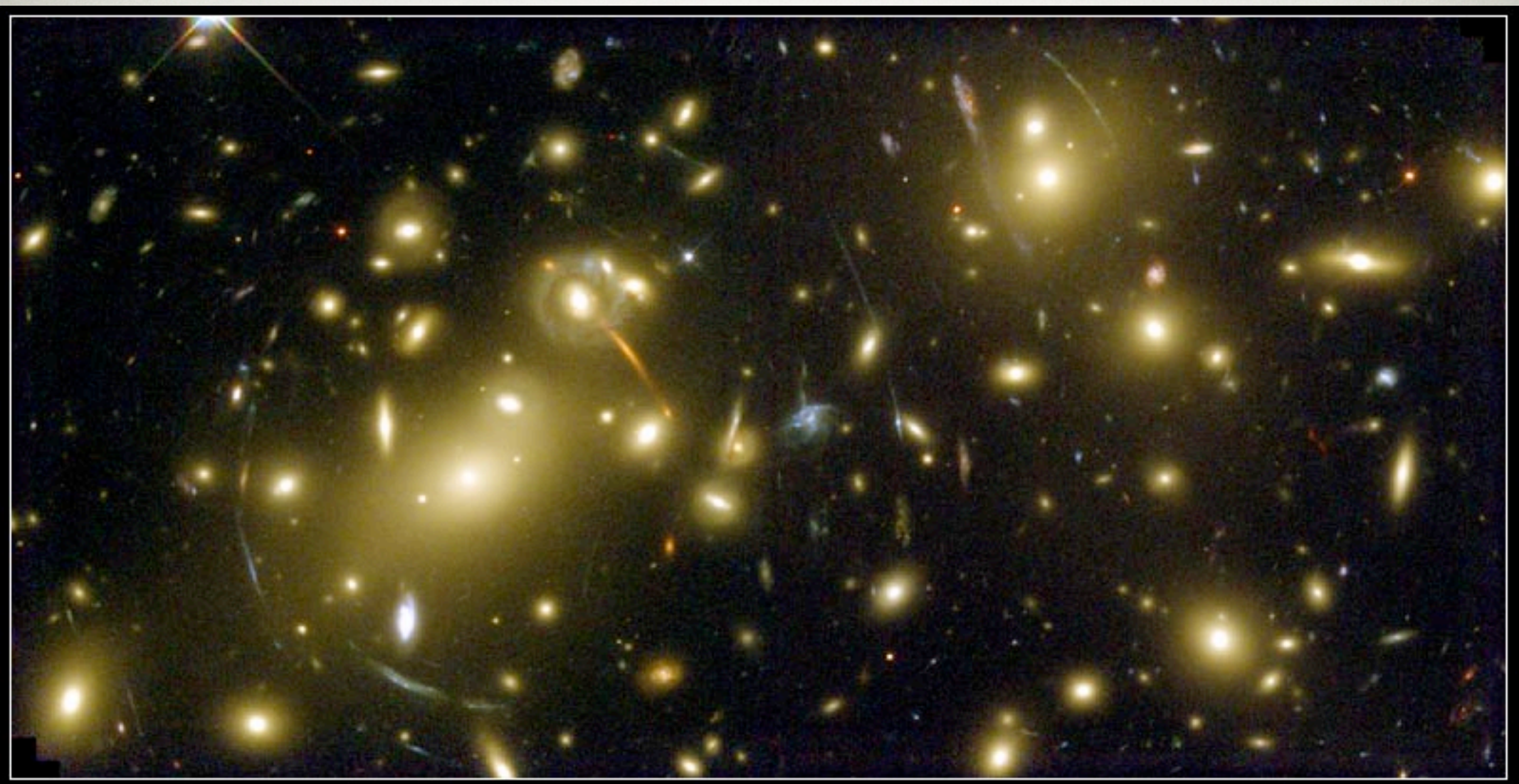
- Count clusters as a function of mass and redshift
- 20,000 clusters to z = 1
- 3 techniques for cluster selection and mass estimation
  - optical galaxy counts
  - weak lensing
  - SZ effect
- Cross compare these to reduce systematics
- Use mass function shape and cluster correlation function.





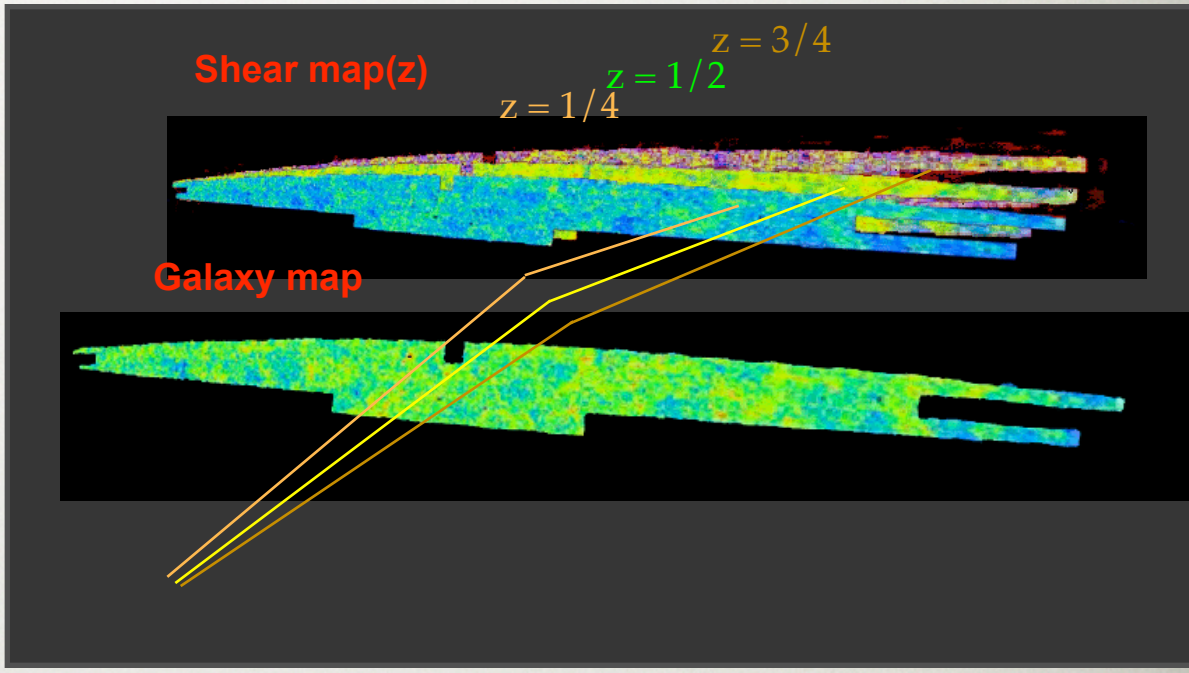


IV. Weak Lensing



Lensing Cosmography

- The strength of weak lensing by the same foreground galaxies changes with the distance to the background galaxies.
  - Measure amplitude of shear vs. z
  - shear-galaxy correlations
  - shear-shear correlations
- DES will
  - Image 5000 sq-degrees
  - Photo-z accuracy of $\delta z < 0.1$ to $z = 1$
  - 10-20 galaxies/sq-arcminute



DES and Dark Energy

- Individually these 4 key projects each give ~5-10% measurements of w.
  - Combined they will push 1%
- Is the Dark Energy a cosmological constant?
  - maybe, if w = -1.0, NO if not
- Is the Dark Energy a modification to gravity?
  - if geometry projects (SN and galaxy distribution) disagree with structure growth projects (cluster counts and weak lensing), then YES

Dark Energy

- These are exciting times to be an observational cosmologist.

- We are working on fundamental physics, and the work is observation driven.